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U.S. 101 MP 111.34 Unnamed Tributary to Stevens Creek (WDFW ID: 990731) Preliminary Hydraulic Design Report

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1 Introduction

To comply with United States et al. vs. Washington et al. No. C70-9213 Subproceeding No. 01-1 dated March 29, 2013 (a federal permanent injunction requiring the State of Washington to correct fish barriers in Water Resource Inventory Areas [WRIAs] 1–23), the Washington State Department of Transportation (WSDOT) is proposing a project to provide fish passage at the United States Highway 101 (U.S. 101) crossing of the project stream to Stevens Creek at Mile Post (MP) 111.34. This existing structure on U.S. 101 has been identified as a fish barrier by the Washington Department of Fish and Wildlife (WDFW) and WSDOT Environmental Services Office (ESO) (site identifier [ID] 990731) and has an estimated 3,811 linear feet (LF) of habitat gain.

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Per the injunction, and in order of preference, fish passage should be achieved by (1) avoiding the necessity for the roadway to cross the stream, (2) use of a full-span bridge, or (3) use of the stream simulation methodology. WSDOT evaluated the crossing as defined in the injunction. Avoidance of the stream crossing was determined not to be viable given the location of the highway and the need to maintain this critical transportation corridor. WSDOT Headquarters (HQ) Hydraulics recommends that the replacement structure should be designed to meet the WDFW unconfined bridge criteria, as described in the 2013 WDFW Water Crossing Design Guidelines (WCDG).

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The crossing is located north of Humptulips, in WRIA 22. The highway generally runs in a northeast–southwest direction at this location and is a little over 1,000 feet (ft) from the confluence with Stevens Creek. This project stream generally flows from east to west beginning 1 mile east of the U.S. 101 crossing (Figure 1).

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The proposed project will replace the existing 48-inch (in) diameter, 87-foot-long, round, corrugated metal pipe (CMP) culvert with a structure designed to accommodate a minimum hydraulic opening of 28 feet. A specific structure type will be determined during a subsequent phase of the design. The proposed structure is designed to meet the requirements of the federal injunction using an appropriate methodology as described in the 2013 WDFW *Water Crossing Design Guidelines* (WCDG) (Barnard et al. 2013). This design also follows the WSDOT *Hydraulics Manual* (WSDOT 2019) with supplemental analyses as noted.

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A draft Preliminary Hydraulic Design (PHD) report was prepared in 2020 by WSDOT and HDR Engineering, Inc. under Agreement Number Y-12374 between HDR and WSDOT Environmental Services Office. WSDOT received review comments on the draft PHD report from WDFW and the Quinault Indian Nation (QIN). As part of Kiewit's Coastal-29 Team of the US 101/SR 109 Grays Harbor/Jefferson/Clallam, Remove Fish Barriers Project under a Progressive Design-Build (PDB) contract between Kiewit and WSDOT, Kleinschmidt Associates (KA) reviewed the draft PHD report, updated the hydraulic modeling and design, addressed WDFW and Tribe comments, and prepared this Draft Final PHD report using material in the draft PHD report as a starting point. Responses to WDFW and Tribe comments are included in Appendix J. While HDR's original field observations and measurements, and selected figures have been retained in this report, all writing and analyses in the draft PHD report have been reviewed, edited, and updated where determined necessary.

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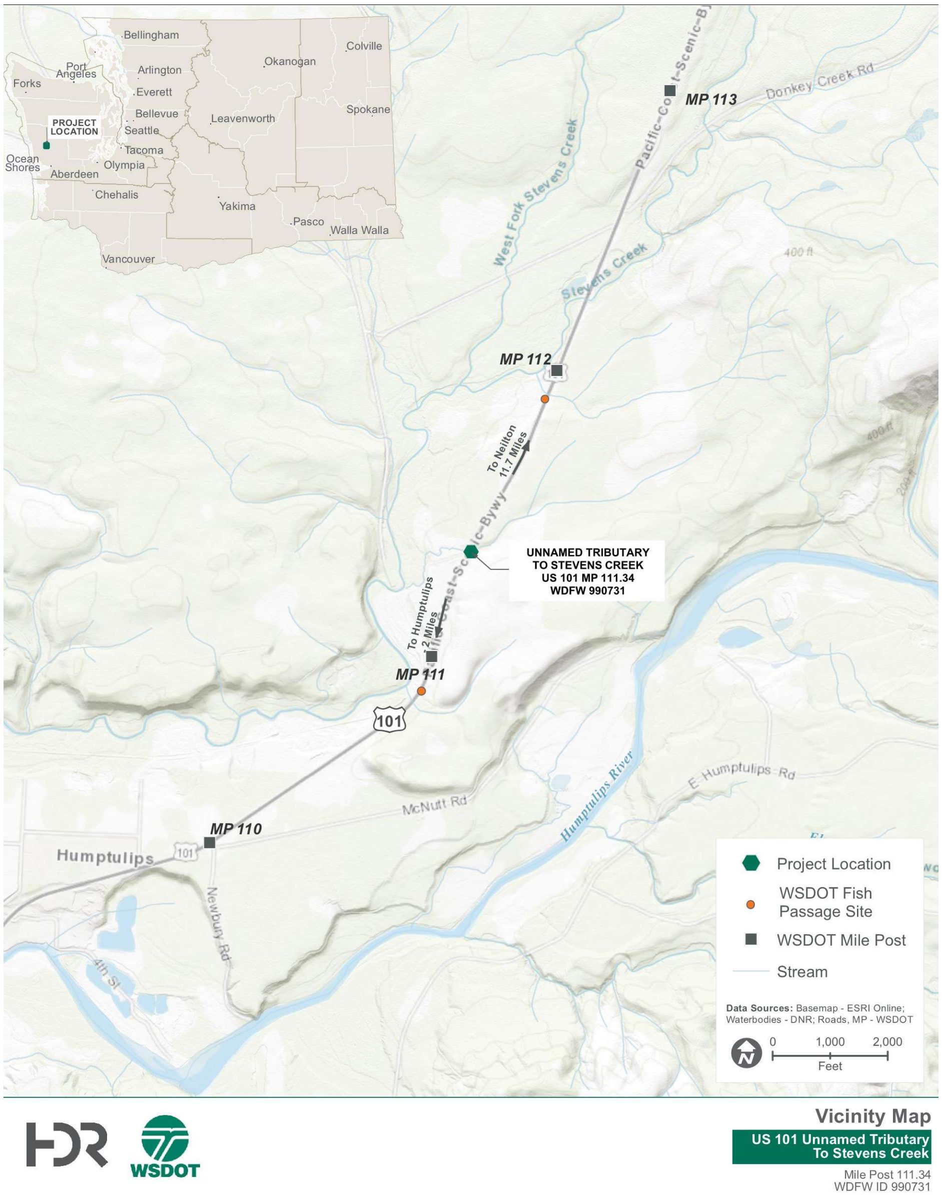

Figure 1: Vicinity map

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2 Watershed and Site Assessment

The existing site was assessed in terms of watershed, land cover, geology, floodplains, fish presence, observations, wildlife, and geomorphology. This was performed using desktop research including aerial photos; resources such as the United States Geological Survey (USGS), Federal Emergency Management Agency (FEMA), and WDFW, past records like observation and fish passage evaluation; and site visits.

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2.1 Watershed and Land Cover

The project stream is located approximately 1.5 miles north of the community of Humptulips and is a tributary to Stevens Creek, with the confluence located approximately 0.3 miles downstream of US 101. Stevens Creek is a tributary to the Humptulips River. The eastern tip of the watershed originates on a steep hillside, but most of the drainage is relatively flat lowland terrain sloping toward the project site. The watershed is presently mostly forested, with drainage affected by U.S. 101 and a network of forest roads. The 2016 National Land Cover Database (NLCD) map (Figure 2) shows land cover at that time to consist primarily of evergreen forest and scrub/shrub (Table 1). The Grays Harbor County Assessor's Office web mapping database indicates the stream flows through various parcels owned by a timber company. Timber harvest has occurred as a patchwork of clearcuts across the basin over time. A review of historical aerial photographs ranging from 1953 to 2017 downloaded from USGS Earth Explorer indicates the basin consisted of dense forest ca. 1953, and that various areas in the watershed were rotationally clear cut starting in the 1980s. In 1990 more than half of the watershed was clear cut. Timber in this watershed has since regrown. Prior to 2005 and the implementation of Washington's Forest Practices Habitat Conservation Plan, timber harvest occurred without leaving a functional riparian management zone.

2.2 Geology and Soils

The basin's surficial geology was mapped at a 1:62,500 scale (Rau 1984) as obtained from the Washington State Department of Natural Resources (WDNR) Geologic Information Portal (Washington Division of Geology and Earth Resources, 2016). The watershed is composed solely of old (pre-Wisconsin) alpine glacial drift (unit Qapw (2)) as shown in Figure 2. Quaternary alluvium (Qa) is mapped within the Sevens Creek floodplain. No landslide hazards were identified in the WDNR Geologic Information Portal within the project basin (Washington Geological Survey, 2020a, and 2020b). According to Thackray's (2008) interpretation of glacial stratigraphy in the area, multiple glacial advances crossed this region, depositing mostly outwash, but also leaving deposits of compacted glacial till, moraines, and interglacial deposits. The youngest deposits consist of outwash plains and reworked channels. Interpretation of LiDAR topography suggests that Stevens Creek is an underfit stream occupying erosional channels (or reworked outwash channels) and is incised through a surrounding outwash plane (brown and white elevated surfaces; Figure 4).

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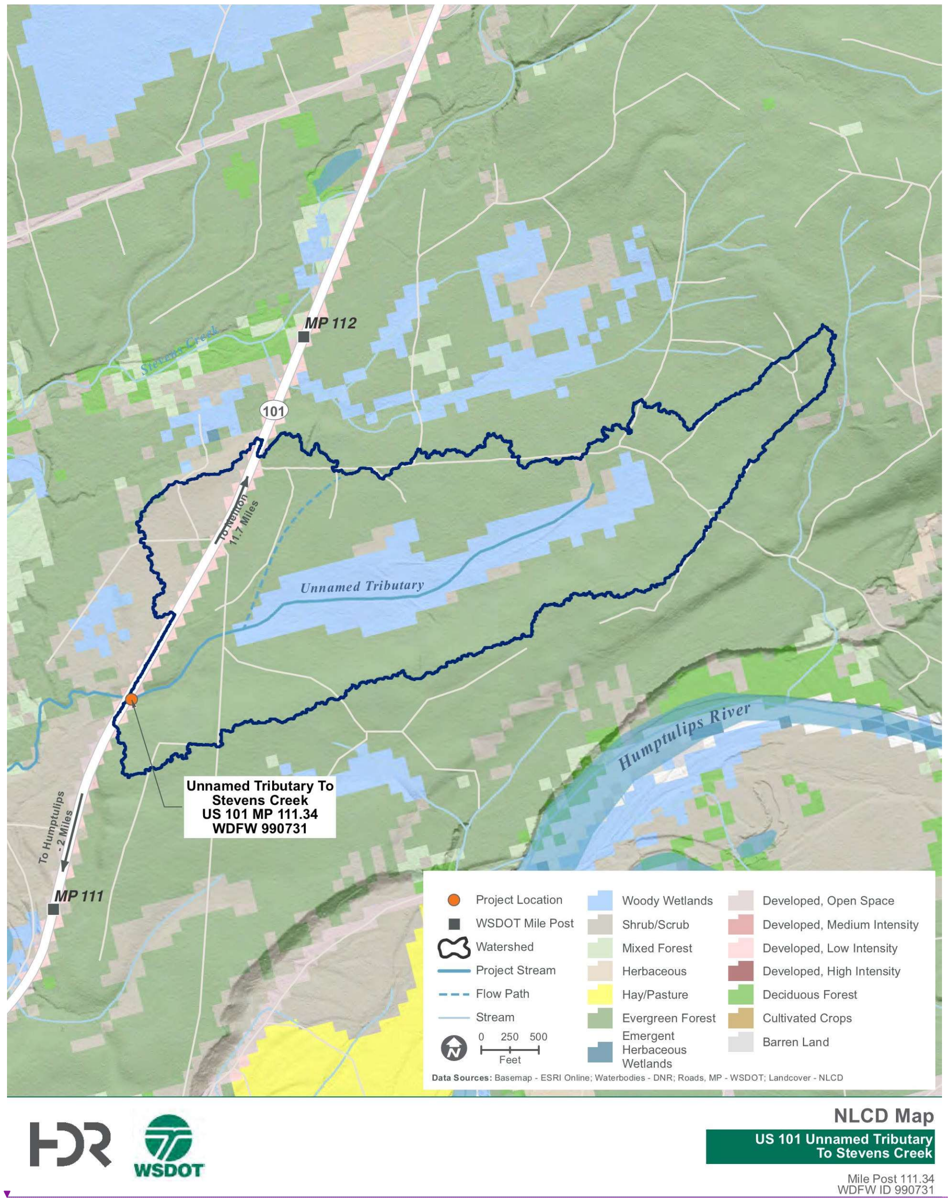

Figure 2: Land cover map (NLCD 2016)

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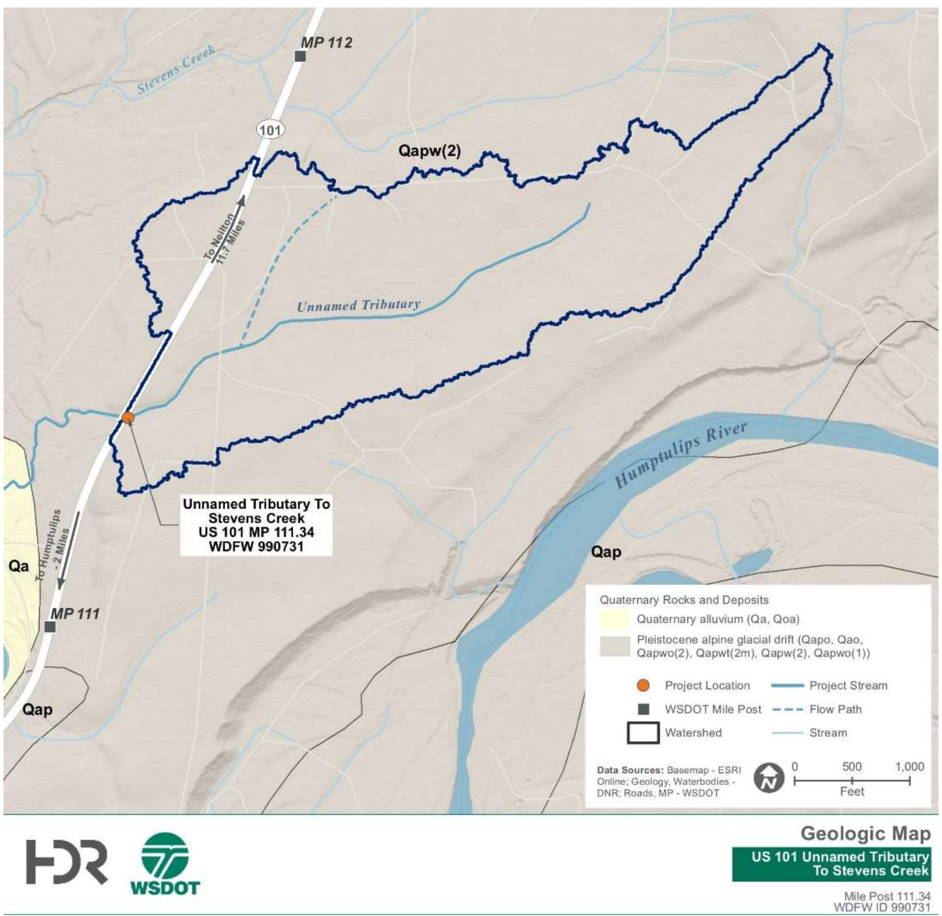
Table 1: Land cover

Land cover class	Basin coverage (percent)
Evergreen forest	72.5
Developed	3.2
Woody wetlands	17.2
Scrub/shrub	7.1



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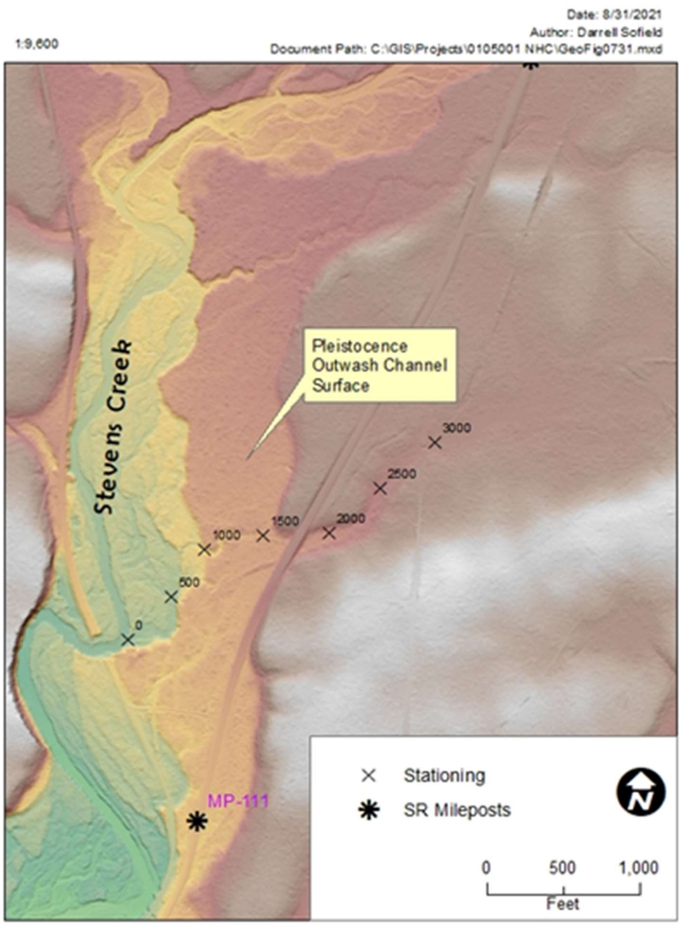

Figure 4: Lidar-based topographic figure of the project site shows Stevens Creek, stationing for the project stream, Pleistocene outwash channels, and uplands

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The glacial history of basin controls the profile of the project stream, which drains what is interpreted to be a pre-Wisconsin glacial outwash plain (238-270 ft) before downcutting an arroyo into the eastern bank (40 ft of relief) of an erosional channel that extends upstream of the US 101 crossing. Below the crossing, the creek flows across the terraced Pleistocene outwash channels (low gradient and weathered); after crossing these outwash terraces, the creek descends steeply to join the modern alluvial floodplain of Stevens Creek. A hardpan was observed in the channel. The hardpan's consistency ranged from clayey silt to silty sand, to stiff gravelly silt. A Geotechnical Boring (WSDOT 2020) logged sandy silt with gravel below the channel. It has the same color and texture of the hardpan exposed in the channel. A relatively stiff, unweathered, silty sand with gravel was observed at depth 210-190 ft elevation, where the boring was completed.

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2.3 Floodplains

The project area spans FEMA Flood Insurance Rate Maps (FIRMs) 53027C0275D and 53027C0460D, both effective February 3, 2017 (FEMA 2017). Based on the FIRMs, the project area is located in Zone X (unshaded). An unshaded Zone X represents areas of minimal flood hazard from the principal source of flooding in the area and is determined to be outside the 0.2 percent annual chance floodplain. Approximately 1,000 feet downstream (DS) of the project, the project stream is in Zone A, indicating that it is subject to inundation by the 1 percent annual chance flood, but no base elevations have been determined. See Appendix A for flood zone information obtained from the FEMA website (FEMA 2017).

2.4 Site Description

The project stream is a tributary to Stevens Creek, which flows past WDFW's Humptulips Salmon Hatchery and into the Humptulips River. The WDFW online fish passage database does not list any impassable barriers between the project culvert and the confluence of Stevens Creek with the Humptulips River. The existing culvert was documented by WDFW to have an estimated 33 percent passability as controlled by slope, which controls both depths and velocities in the culvert. In addition, the outlet of the culvert is perched at low flow. WDFW surveyed the project stream upstream of the project site and estimated 3,811 linear feet of potential habitat gain (WDFW 2021).

2.5 Fish Presence in the Project Area

The Statewide Washington Integrated Fish Distribution (SWIFD) (2020) online database documents only resident rainbow trout (*Oncorhynchus mykiss*) in the project stream. The small size likely precludes spawning of larger salmonid species. Habitat in the vicinity of the culvert appears to be unsuitable for year round use by juvenile salmonids, as the stream was observed to dry during summer 2021 in the vicinity of the culvert. However, salmonids approximately 4 to 6 inches long were seen by the Stream Team Fisheries Biologist in a pool at the first logging road crossing upstream in July and August 2021. A patch of potential spawning gravel was also observed on the downstream side of the crossing bridge. Thus, it is possible that the stream may be used by Coho Salmon (*O. kisutch*). Stevens Creek is documented to contain Coho, fall Chinook (*O. tshawytscha*), and Chum (*O. keta*) salmon, plus Steelhead (*O. mykiss*), bull trout (*Salvelinus confluentus*), and coastal cutthroat trout (*O. clarkii clarkii*) (SWIFD 2020; WDFW 2020a, 2020b; StreamNet 2020).

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Fall Chinook juveniles migrate out to the ocean in their first year and do not overwinter in freshwater tributaries, so they are unlikely to disperse up the project stream to the project reach. However, because fall Chinook salmon are documented to occur in Stevens Creek and there is no barrier to the project stream, it is possible that some juveniles may move up into the project stream during migration. Habitat conditions in the tributary are poor and unlikely to be used by Chinook, but the presence of a few juvenile individuals during seasonal high flows is possible. Chinook that inhabit the watershed are part of the Washington Coast evolutionary significant unit and are not currently listed under the Endangered Species Act (ESA).

Bull trout have more specific habitat requirements than most other salmonids; in particular they require cold water (46 degrees Fahrenheit or below) for spawning and egg incubation, and abundant instream cover for rearing (Rieman and McIntyre 1993). They typically spawn and rear in the cold, clear tributaries in the upper portions of watersheds. The project stream appears to have seasonally intermittent flows and lacks the cool flowing, clear stream characteristics for bull trout habitat. Therefore, bull trout are not expected to be present in the project stream and the project reach.

Coho use small streams and are widespread in small rivers throughout coastal Washington, and can be found in virtually every small coastal stream with year-round flow. They have been found in the vicinity of the project stream crossing previously (WDFW 2021). Juveniles overwinter for at least 1 year throughout rivers and tributaries prior to migrating out to the ocean (Wydoski and Whitney 2003). Juveniles can thus be expected to use the project reach, although summer habitat may be limiting for this species when portions of the stream go dry (see section 3.0).

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Chum salmon also are widespread, use coastal streams with low gradients and velocities and the lower reaches of larger rivers, and often use the same streams as coho, but chum generally spawn closer to salt water. Chum fry do not rear in fresh water for more than a few days. Shortly after they emerge, chum fry move downstream to the estuary and rear there for several months before heading out to the open ocean (Wydoski and Whitney 2003). Spawning habitat in the project stream is poor, and it is unlikely that chum salmon use the project reach; however, a few juveniles could possibly be present in lower reaches during spring high flows prior to outmigration.

Steelhead (*Oncorhynchus mykiss*) are also present throughout many coastal streams and rivers. They generally prefer fast water in small to large mainstem rivers and medium to large tributaries. The project stream is too small and the habitat is unsuitable to support steelhead spawning. Steelhead are documented in Stevens Creek, and rainbow trout (the resident form of steelhead) are documented in the project stream (SWIFD 2020). Steelhead that inhabit the watershed are part of the Southwest Washington distinct population segment (DPS) and are not currently listed under the ESA. There is no barrier from Stevens Creek to where the project is located. Therefore, juvenile steelhead are likely present in the project stream during overwintering and seasonal high flows.

Coastal cutthroat trout are also widespread throughout small streams in western Washington and are likely also present in the project stream. They seek smaller streams with minimal flow and small gravel substrate including sand. They can be anadromous and rear in streams for 2 to 3 years, or be resident and remain entirely in fresh water.

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Table 2 provides a list of salmonid fish species that potentially occur in the project stream and that could be affected by the culvert crossing.

Table 2: Native fish species potentially present within the project area

Species	Presence (presumed, modeled, or documented)	Data source	ESA listing
Washington Coast fall Chinook salmon *(Oncorhynchus tshawytscha)*	Presumed (documented in Stevens Creek)	SWIFD 2020, WDFW 2020a, WDFW 2020b	Not warranted
Southwest Washington DPS[a] steelhead (*Oncorhynchus mykiss*)	Presumed (documented in Stevens Creek)	SWIFD 2020, WDFW 2020a, WDFW 2020b	Not warranted
Coho salmon (*Oncorhynchus kisutch*)	Presumed (documented in Stevens Creek)	SWIFD 2020, WDFW 2020a, WDFW 2020b	Not warranted
Chum salmon (*Oncorhynchus keta*)	Presumed (documented in Stevens Creek)	SWIFD 2020, WDFW 2020a, WDFW 2020b	Not warranted
Coastal cutthroat (*Oncorhynchus clarkii clarkii*)	Presumed	SWIFD 2020	Not warranted

a. ESA = Endangered Species Act.
b. DPS = distinct population segment.

2.6 Wildlife Connectivity

A Wildlife Connectivity memo from WSDOT's Environmental Services Office was not required for this site.

2.7 Site Assessment

A site assessment was performed of fish habitat conditions, hydraulic and geomorphic characteristics, and the culvert based on field visits, WDFW's barrier inventory report (WDFW 2021), and a WSDOT survey. Two initial visits occurred in 2020, with subsequent visits postponed until 2021 after the Covid-19 pandemic had begun to subside.

2.7.1 *Data Collection*

Site visits were performed on five occasions to collect data and observe conditions and characteristics influencing the hydraulic design:

- HDR visited the project site on June 25 and July 28, 2020, to collect pertinent information to support development of an initial design, including bankfull width (BFW) measurements, and

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characterizations of instream fish habitat and floodplain conditions. Channel substrates, large wood accumulations and floodplain vegetation were characterized.

- Kleinschmidt-R2 and Kiewit visited the site on June 1, 2021 to corroborate the initial data collection findings, review the representativeness of the BFW and channel substrate measurements, and identify additional data collection needs.
- Kleinschmidt-R2 and Kiewit visited the site on June 15, 2021 to collect a bulk substrate sample, characterized the hydraulic effect of natural downstream in-channel flow obstructions as it would affect hydraulic modeling predictions, and measure the typical size of mobile wood pieces upstream of the culvert as they would affect the determination of minimum freeboard requirements.
- Kleinschmidt-R2 and NHC visited the site on July 13, 2021 to support an evaluation of the long term vertical stability of the channel.

Field reports are presented for each visit in Appendix B. BFWs are summarized in Section 2.8.2

WSDOT also surveyed the site in August 2020. The survey extended approximately 160 feet upstream and 210 feet downstream of the crossing. The reach surveyed comprises the project reach within which most data were collected and observations made for use in developing the design. Survey information included break lines defining stream bank toes and tops and overbank areas along the channel. The data were used to generate hydraulic models and evaluate geomorphology during development of the hydraulic design.

2.7.2 *Existing Conditions*

2.7.2.1 Culvert

The existing structure is a 87-foot-long, 48-inch-diameter circular corrugated metal pipe (CMP) culvert. The culvert has a gradient of 1.2 percent with the inlet invert elevation at 222.4 feet and the outlet invert elevation at 221.3 feet. Road fill depth is approximately 20 feet above the existing culvert based on WSDOT survey data, The inlet has 45-degree wingwalls mitered to the embankment and is round, but transitions to a concrete box culvert in the section under the roadway (Figure 5). The box transitions back to a round outlet that discharges onto a concrete apron (WDFW 2021). The outlet of the culvert is perched about 1 foot above the channel, and the headwalls are mitered to the slope of the road embankment (Figure 6). There is a scour pool below the apron and substrate in the pool is composed primarily of fines.

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The culvert has not been identified as a chronic environmental deficiency or failing structure. WSDOT has not noted any maintenance problems.

Figure 5: Culvert inlet (left) and inside of culvert (right)

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Figure 6: Culvert outlet

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2.7.2.2 Stream

The channel cross-section upstream of the crossing varies between being not well defined, flowing through low relative elevation wetland complexes with multiple smaller low flow paths, and intervening sections with a more defined, single thread channel cross-section. The reach is generally overgrown with brush and fallen timber at numerous locations, with abundant large woody material (LWM) present in the channel and spanning the banks (Figure 7). Much of the fallen timber likely reflects wind throw of residual trees left along the channel margins during previous clearcutting. Water drops over some pieces (Figure 8). Substrates vary from mostly silt to heavily embedded small gravel (Figure 9). Shrubs and ferns are present on the floodplains, stream banks, and within the channel.

Figure 7: Example of LWM spanning channel in reference reach

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Figure 8: Water surface drop in reference reach

Figure 9: Small gravels found upstream of culvert

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The channel is less sinuous and straighter downstream of the culvert. Vegetation is dominated by abundant shrubs and trees on the stream banks and on the floodplain. There is extensive LWM and smaller wood present within a more confined channel within the first 100 feet downstream of the culvert outlet, with many large logs forming jams that present significant blockage of in-channel flows (Figure 10). The channel substrate is predominantly fines and some hardpan, but there are more distinct patches of larger gravel present compared with upstream (Figure 11). The channel becomes less confined more than 100 feet downstream of the culvert outlet, with several larger channel spanning, fallen trees that the stream flows under (Figure 12). Patches of gravel are more evident here than upstream. Both the channel and banks are made of fine material.

Figure 10: Examples of woody debris in the channel downstream of the culvert

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Figure 11: Pocket of gravel under debris jam (largest material measured at 2.5-inch diameter)

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Figure 12: Reference Reach downstream of culvert

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2.7.2.3 Floodplain

The channel is generally less confined upstream with greater floodplain connectivity than downstream of the culvert, with several locations where water flows can spread out over wetland areas through multiple high flow channels at relatively low flows. These sections likely act to limit upstream passage of adult salmon to higher flows during freshets. The channel is more entrenched and forested within the first 100 feet below the culvert. Farther downstream, bankfull depths are shallower and the adjacent floodplain is vegetated more with shrubs and becomes more hydrologically connected.

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2.7.3 ***Fish Habitat Character and Quality***

Upstream of the U.S. 101 crossing, the project stream flows through a previously logged, conifer-dominant mixed forest consisting of Sitka spruce (*Picea sitchensis*) and western hemlock (*Tsuga heterophylla*), with some Douglas fir (*Pseudotsuga menziesii*), red alder (*Alnus rubra*), and western red cedar (*Thuja plicata*). There is a dense shrub understory with native species including evergreen huckleberry (*Vaccinium ovatum*), salmonberry (*Rubus spectabilis*), vine maple (*Acer circinatum*), salal (*Gaultheria shallon*), and several species of ferns. The mature forest and shrub cover provide good shading, nutrient inputs, and potential for LWM recruitment.

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WDFW (2021) estimated 3,811 LF of potential habitat, with 32,824 square feet (SF) available for salmonid rearing upstream of the crossing. Large downed logs and woody material are abundant within the stream channel and banks throughout the upstream reach. Many logs span across the channel banks well above the water levels in the stream Figure 5 above). There were 23 significant pieces of LWM in and across the channel within the surveyed reach, and a few debris jams. These logs generally ranged from 8 to 36 inches in diameter and also included some rootwads. The abundant LWM provides habitat complexity and cover for salmonids using this reach for rearing and migration during high flow periods. These functions are limited during low flow periods when shallow water and LWM debris jams impede fish movement through this reach, and when the stream in the vicinity goes dry in the late summer months.

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The stream is small and shallow, and instream habitat consists predominantly of shallow glides with few small pools associated with LWM. The stream can go dry during the summer, with standing water in isolated larger pools. A large pool exists at the upstream logging road crossing and was seen by the Stream Team in the summer of 2021 to hold fish. Substrate in the reach is predominantly fines with some organic debris and vegetation. Spawning habitat is accordingly generally absent in most of the reach, although some potential spawning gravels were seen under the logging road crossing.

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The downstream reach also flows through a previously logged area, but the riparian corridor has fewer mature trees and the canopy is more open than in the upstream reach. The mature trees consist primarily of Sitka spruce and Douglas fir, with some alders and willows (*Salix* spp.). The mature tree cover is most dense near the road embankment by the culvert outlet and provides shading for the stream. Downstream the mature trees are sparse and the banks are covered by a dense shrub layer, which provides limited shading for the stream. The shrub layer included predominantly native species such as raspberry, evergreen huckleberry, salmonberry, vine maple, spirea (*Douglas Spiraea*), and ferns. Non-native Himalayan blackberry (*Rubus armeniacus*) was also present in some of the open areas along both banks. The reduced riparian corridor also limits potential LWM recruitment. LWM is present throughout the downstream reach, but is less abundant than upstream. There were 10 pieces of significant LWM across and within the bankfull channel. These logs generally ranged from 8 to 30 inches in diameter. Several downed trees lying across the channel had many branches extending into the stream, causing debris racking. The smaller downed trees near the culvert outlet at the base of the road prism had a large number of branches in the channel and created a dense debris jam, creating an impediment to fish passage during low flows.

The stream channel in the downstream reach is fairly straight, and was seen to dry up in summer 2021. When flowing, the channel farther below the culvert consists predominantly of shallow riffle and glide habitat over some embedded gravels and fines. Pool habitat is generally lacking throughout the downstream reach except in the vicinity of the culvert outfall. Suitable spawning habitat for salmonids is lacking in the downstream reach and the habitat is primarily suited to be a migratory corridor during periods of higher flows. Some limited rearing habitat is present, and instream cover is provided by the woody material, but the lack of pools and habitat complexity limit this function.

2.8 Geomorphology

Geomorphic information provided for this site includes selection of a reference reach, the basic geometry and cross sections of the channel, stability of the channel both vertically and laterally, and various habitat features.

2.8.1 *Reference Reach Selection*

Two sections of stream, one approximately 40 to 90 feet upstream (Figures 7, 8) and the other 100-150 feet downstream of the culvert (Figure 12) were selected as reference reaches representative of the natural stream channel with the least anthropogenic influence (Figure 13). Both reaches are located within a longer, approximately 1.2% grade reach. The reference reaches were relied on primarily for measuring bankfull dimensions for informing the design of the hydraulic opening width and the cross-section morphology of the constructed channel outside of the replacement structure footprint. The reference reach morphology was not used to design cross-section shape and planform underneath the replacement structure because vegetation controlling bank stability cannot generally grow there. The channel in the reference reaches does not appear to be incising and thus was judged to be in Stage I of Schumm et al.'s (1984) Channel Evolution Model. Areas surrounding the reference reaches where the flow disperses across the valley bottom are characterized as Stage Zero wet woodland in the framework of Cluer and Thorne (2014).

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2.8.2 *Channel Geometry*

Channel planform is generally straight upstream and downstream of the crossing, with minor meandering. A total of seven BFW measurements were taken during three site visits. Three measurements were made in 2020 using a tape in the upstream reference reach, and two in the downstream reach (Table 3). The upstream measurements may have been influenced over the long term by backwatering from the culvert and so were not used in the final calculation of a design bankfull width criterion. The first two measurements downstream were performed in the confined section and are generally lower than values measured by the Quinault Indian Nation (QIN; Table 3). Two additional measurements were performed downstream in 2021 by surveying the cross-section profile (Figure 14). The QIN measurements were mostly larger than the measurements in Table 3. However, because the proposed structure will be wider than would be derived based on BFW, WSDOT has accepted the QIN average BFW value of 14.4 feet for use as a stream channel design criterion (Table 3). Concurrence of the BFW of 14.4 feet was reached during the July 12, 2021 meeting with WSDOT, WDFW and QIN.

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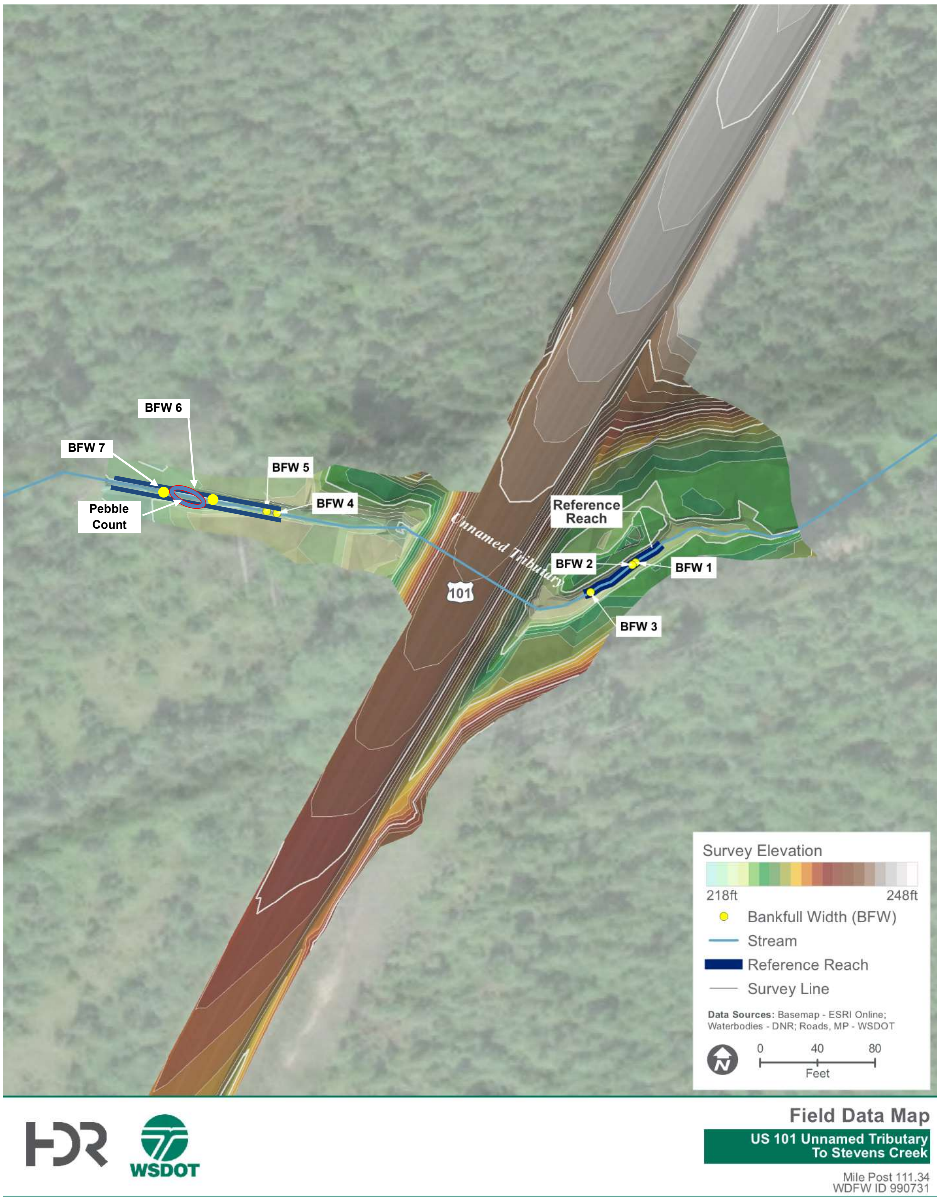

Figure 13: Reference reach and locations of BFW measurements and substrate sampling

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Table 3: Bankfull width (BFW) measurements

BFW #	Width (ft)	Included in Average	Concurrence notes
1	11.0	No	QIN measured 12 ft, 17 ft, 15 ft, 13 ft, 15 ft
2	11.2	No	
3	14.0	No	
4	10.2	No	
5	9.0	No	
6	12.6	Yes	
7	12.8	Yes	
Average	12.7		QIN average of 14.4 feet adopted by WSDOT

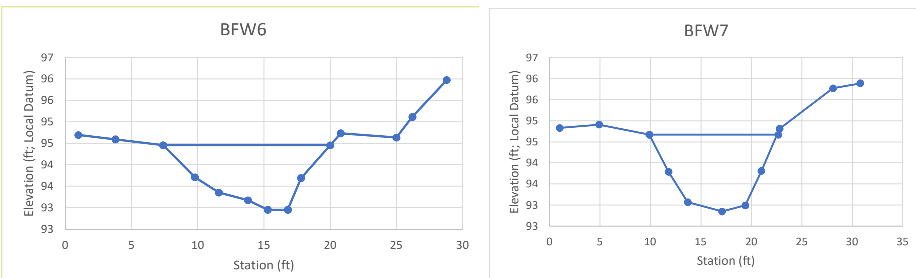

Figure 14: Cross section profiles surveyed in 2021 for BFW determination

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2.8.3 *Sediment*

This is a limited gravel system, and the channel shows few indications of active gravel transport. Very little coarse sediment was observed, and sections of the channel bed were composed of hardpan, no sediment. A pebble count was performed in 2021 in the downstream reference reach between the two new BFW measurement cross-sections (Table 4). Gravel observed throughout the channel and reference reach was observed to be generally less than 2.5 inches in size (Figure 15).

Table 4: Sediment properties downstream of project crossing

Particle size	Pebble Count Diameter (in)
D_{16}	0.4
D_{50}	0.8
D_{84}	1.4
D_{95}	1.6
D_{MAX}	2.4

Figure 15: Representative gravel substrate in reference reach downstream of culvert

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2.8.4 *Vertical Channel Stability*

Vertical channel stability was assessed considering land use, longitudinal channel elevation profiles of the project stream, topographic models, and field observations. It may be assumed that historical land use in the watershed caused changes in sediment supply, wood loading, and runoff to a greater extent than what may be expected in the future. This is because there is a low potential of landslides or debris flow type sediment delivery in the watershed (Section 2.2) and because we may expect declining influence of future forest harvest activities. Historical logging within the riparian zone and clearcut logging likely created historic spikes in sediment supply and greater runoff (Section 2.1). With more conservative timber harvest practices and associated protective buffer width requirements in effect since 2005, future sediment yield is expected to decline and return to a lower background level. However, in this reach a lack of upstream transport capacity likely has, and will continue to, limit the supply of coarse gravel to the crossing location.

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Longitudinal profiles were developed from 2019 LiDAR data (Figure 16; USGS and Quantum Spatial 2019). 2020 survey data collected by WSDOT indicates that the channel elevations in the LiDAR data profile are higher than actual, but the bias appears to be consistent away from the road prism. The profiles were used to identify significant landmarks and breaks in the channel gradient that would influence spatial variation in sediment transport and deposition patterns that could be associated with a potential for future aggradation or degradation in the vicinity of the replacement structure. This knowledge is primarily important for designing the streambed longitudinal profile within the area of project effects, and the freeboard elevation and foundation depth of the replacement structure. The LiDAR profile presented in Figure 16 extends approximately 4,000 feet upstream and 2,000 feet downstream from the project culvert. The overall convexity of the channel profile and position of slope breaks are related to control that underlying geology exerts on the stream. On the glacial outwash plateau, the slope is low (around 0.5 percent), and includes a ridge that may be a defunct beaver dam. The slope increases at the edge of this plateau at a distance of about 1,300 feet upstream of the culvert. The gradient remains consistent and averages 1.4 percent on both sides of US 101.

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Approximately 340 feet downstream of the culvert, there is a slope break where the channel begins to incise within a 20-foot high terrace of outwash channel deposits over a steeper (around 2.6 percent) slope. In general, this setting could be associated with potential long term degradation at the culvert location if the steeper downstream profile translates upstream. At this site, however, there are several mitigating factors that lead to concluding the risk of degradation is negligible for this site. The low relative elevation and width of the floodplain downstream, the presence of multiple exposed hardpan grade controls and sporadic gravel armoring, and high channel roughness and debris blockages resulting in reduced velocities all work against a headcut moving upstream and undermining the foundation of a replacement structure. The overall risk of degradation is therefore concluded to be low at this site.

The channel bed consists of hardpan, lag gravels and woody debris, which indicates that reach in the vicinity of the culvert is gravel-limited and has not aggraded sediment in the past. Given that the downstream reach above the slope break is approximately in line with the grade upstream of the culvert, it is inferred that the risk of aggradation from long-term sedimentation is likely to be low at this crossing.

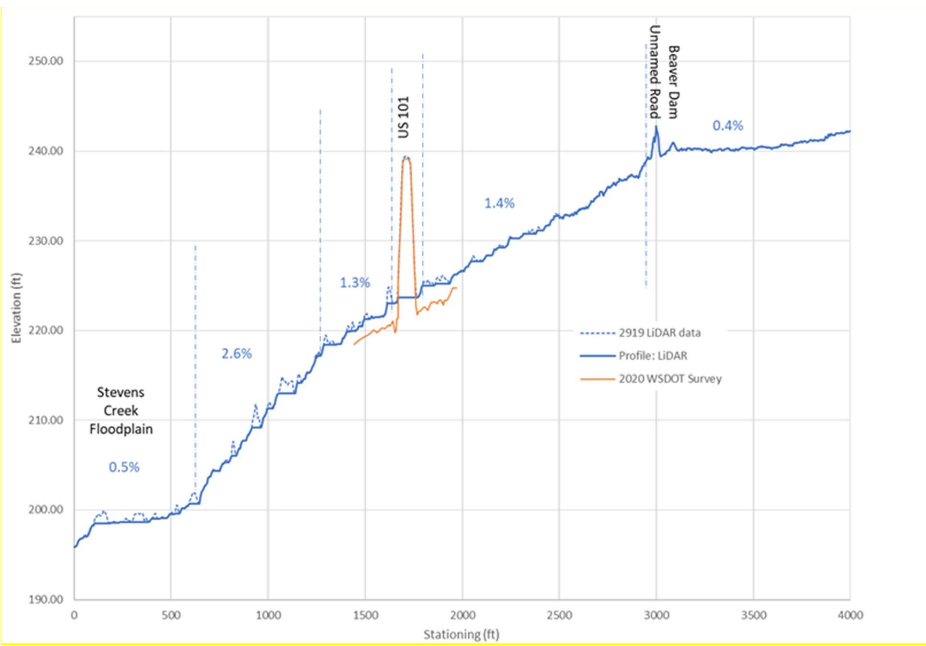

Figure 16: Watershed-scale longitudinal profile, with gradients and 2020 WSDOT Survey Data

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2.8.5 *Channel Migration*

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Channel migration was assessed using historical imagery, modeling results, and field observations. The stream is too small and canopy too thick for aerial photography to be of use for evaluating migration history. Nonetheless, there are several lines of evidence that collectively indicate that the risk of significant channel migration is negligible at this site. Modeling results, survey data, and field observations indicate the channel is generally small, unconfined and relatively straight upstream and downstream of the crossing, with overbank flow occurring at relatively low discharges and thus erosive forces may be expected to be relatively low during floods. The high density of fallen timber and large woody debris slows down velocities during floods, and generally pins the channel in place. These factors all tend to be indicative of stability in channel planform location.

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2.8.6 *Riparian Conditions, Large Wood, and Other Habitat Features*

The forest surrounding the upstream reach is a conifer-dominant mixed forest consisting primarily of Sitka spruce and western hemlock, with some alder and western red cedar. The surrounding conifer forested area is regrowth from previous timber harvests. The riparian corridor of mature trees along the left bank is relatively narrow and is bounded by a replanted timber-harvested area with uniform young trees. The riparian forest along the right bank is bounded by U.S. 101. The shrub understory along the upstream reach is fairly dense and dominated by native species including salmonberry, vine maple, salal, and sword fern (*Polystichum munitum*). Abundant LWM was observed throughout the upstream reach. There were 23 significant pieces of LWM in and across the channel within the reach surveyed by WSDOT. Many large logs formed bridges across the bankfull channel, well above the water surface. These logs generally ranged from 8 to 36 inches in diameter and also included some rootwads.

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The downstream reach flows through a previously timber-harvested area and the riparian corridor has only patches of mature tree cover consisting primarily of Sitka spruce and Douglas fir, with some alder and bigleaf maple near the road. The narrow riparian corridor of mature trees by the surrounding timber harvest areas also limits LWM recruitment, and LWM overall was less abundant than upstream. There were 10 pieces of significant LWM counted across and within the bankfull channel within the surveyed reach. These logs generally ranged from 8 to 30 inches in diameter and included several downed trees lying across the channel that had many branches extending into the stream, creating debris racking. Transport of LWM is limited in this reach because of the low slope and amount of wood and log jams already present in the channel, blocking transportation of wood down the channel.

What appeared to be a defunct beaver dam was found approximately 1,400 feet upstream of the culvert. No signs of recent beaver activity were observed in the project reach, however.

3 Hydrology and Peak Flow Estimates

The project stream drains an ungaged basin, with no long-term historical flow data available. No hydrologic studies, models, or reports were found that summarized peak flows in the basin. Consequently, USGS regression equations (Mastin et al. 2016; Region 4) were used to estimate peak flows at the project stream to Stevens Creek. Inputs to the regression equation included basin size and mean annual precipitation. The project stream has a basin area of 0.35 square mile with a mean annual precipitation of 111.8 inches (PRISM Climate Group 2019). The basin was delineated from LiDAR data acquired from the WDNR's LiDAR Portal (USGS et al. 2012) using Arc Hydro basin delineation tools. The Arc Hydro results and their correlation with topographic data and existing culverts were inspected to confirm the final delineation.

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The resulting regression estimates (Table 5) were evaluated for potential sub-regional bias by comparing regression predictions against estimates derived at selected stream gages in the area using available flow records. A Washington Department of Ecology gage was identified from the Wishkah River, but only USGS gages were found with a sufficiently long period of record (>20 years) in the area to permit evaluating the larger predicted flood peaks (Table 6).

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Peak flow data were analyzed for each gage following the Bulletin 17B methodology for peak flow frequency analysis, using the Hydraulic Engineering Center's Statistical Software Package (HEC-SSP) version 2.2. HEC-SSP uses the Log Pearson Type III distribution for annual peak flows on unregulated streams, fit by the Method of Moments. Distribution parameters were estimated for the 2-, 10-, 100-, and 500-year return intervals based on moments of the sample data (site-specific). Adjustments were made for non-standard data, low outliers, and historical events. The resulting peak flow estimates were compared against the regression estimates using the equations in Mastin et al. (2016), where drainage area and mean annual precipitation estimates were determined using USGS' StreamStats web application. The ratio of gage-based to regression-based estimates was then plotted against drainage area (Figure 17). The results indicate that the regression estimates for smaller basins may be generally comparable to or higher than would be derived using gage data. As corroboration, a modeling exercise performed for Culvert ID 993704 using the MGS Flood model indicated that the regression estimates for a similarly sized, nearby drainage area were higher than values estimated based on a more direct simulation of stormwater rainfall-runoff processes. The regression estimates accordingly appear to be more conservative.

Consequently, the regression estimates in Table 5 were used in design development, to provide a safety factor when designing for flood conveyance, freeboard, channel stability, and scour. For more information on the 2080 predicted 100-year flow determination see Section 7.2.

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Summer low-flow conditions are unknown and high/low fish passage design flows are not included in this analysis. The stream was observed to be dry in mid-July 2021.

Table 5: USGS regression-based estimates of peak flow

Recurrence interval (years)	USGS regression equation (Region 4) (cfs)	Regression standard error (percent)
2	38.6	52.5
10	64.6	50.5
25	76.9	51.7
50	86.6	52.9
100	97.3	54.2
500	119.0	58.0
2080 predicted 100	116.2	

Table 6: Local USGS Gages Used to Evaluate Bias in USGS Regression Predictions

Station #	Gage Name	Years of Record
12039005	Humptulips River Below Hwy 101	2002-2018
12036000	Wynoochee River Above Save Creek Near Aberdeen, WA	1952-2018
12035500	Wynoochee River at Oxbow Near Aberdeen, WA	1925-1952
12035450	Big Creek near Grisdale, WA	1972-1996
12035400	Wynoochee River near Grisdale, WA	1965-2018
12039050	Big Creek near Hoquiam, WA	1949-1970
12039100	Big Creek Tributary near Hoquiam, WA	1949-1968

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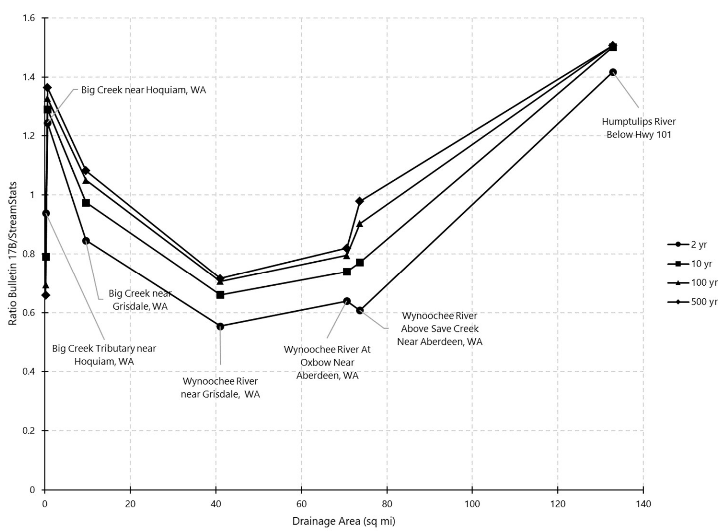

Figure 17: Ratio of gage-based flood peak magnitudes vs. regression-based estimates, plotted against drainage area

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4 Hydraulic Analysis and Design

The hydraulic analysis of the existing and the proposed U.S. 101 project stream crossing was performed using the United States Bureau of Reclamation's (USBR's) SRH-2D Version 3.3.0 computer program, a two-dimensional (2D) hydraulic and sediment transport numerical model (USBR 2019). Pre- and post-processing for this model was completed using SMS Version 13.1.13 (Aquaveo 2021).

Three scenarios were analyzed for determining stream characteristics for the project stream to Stevens Creek : (1) existing conditions with the 48-inch-diameter CMP culvert, (2) estimated natural conditions with the roadway embankment removed within the active floodplain extents, and (3) future conditions with the proposed 20-foot hydraulic opening.

4.1 Model Development

This section describes the development of the model used for the hydraulic analysis and design.

4.1.1 *Topographic and Bathymetric Data*

The channel geometry data in the model were obtained from the MicroStation and InRoads files provided by the Project Engineer's Office (PEO), which were developed from topographic surveys performed by WSDOT in August 2020. The survey data were supplemented with quality level 1 (QL1) LiDAR data with a 3-foot cell size (USGS et al. 2012). Proposed channel geometry was developed from the proposed grading surface originally created by HDR and later updated by Kleinschmidt. All survey and LiDAR information is referenced against the North American Vertical Datum of 1988 (NAVD88) in U.S. Survey feet.

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4.1.2 *Model Extents and Computational Mesh*

The hydraulic model upstream and downstream extents start and end within area surveyed by WSDOT. The detailed survey data are stitched into the LiDAR to incorporate more area outside of the channel. The model boundary starts approximately 160 feet upstream of the existing culvert inlet and ends approximately 210 feet downstream of the existing culvert outlet, measured along the channel centerline. The computational mesh elements are a combination of patched (quadrilateral) and paved (triangular) elements, with finer resolution in the channel and larger elements in the floodplain. The existing-conditions model covers a total area of 136,599 SF, with 8,067 quadrilateral and 49,698 triangular mesh elements (Figure 18). Natural-conditions model covers a total area of 136,599 SF, with 6,865 quadrilateral and 52,242 triangular mesh elements (Figure 19). The proposed-conditions model covers a total area of 132,937 SF, with 7,425 quadrilateral and 48,478 triangular mesh elements (Figure 20).

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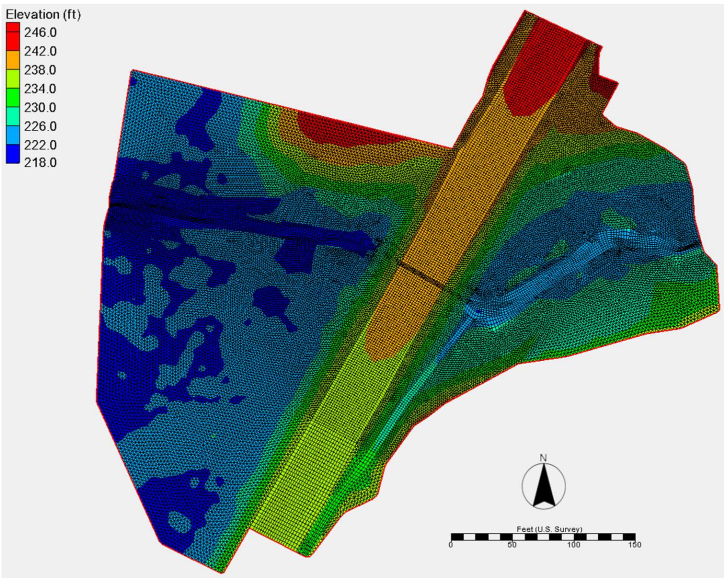

Figure 18: Existing-conditions computational mesh with underlying terrain

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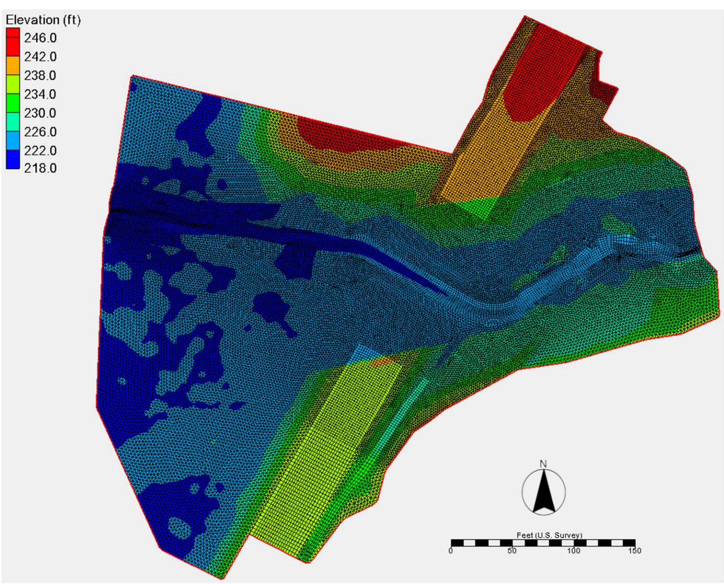

Figure 19: Natural-conditions computational mesh with underlying terrain

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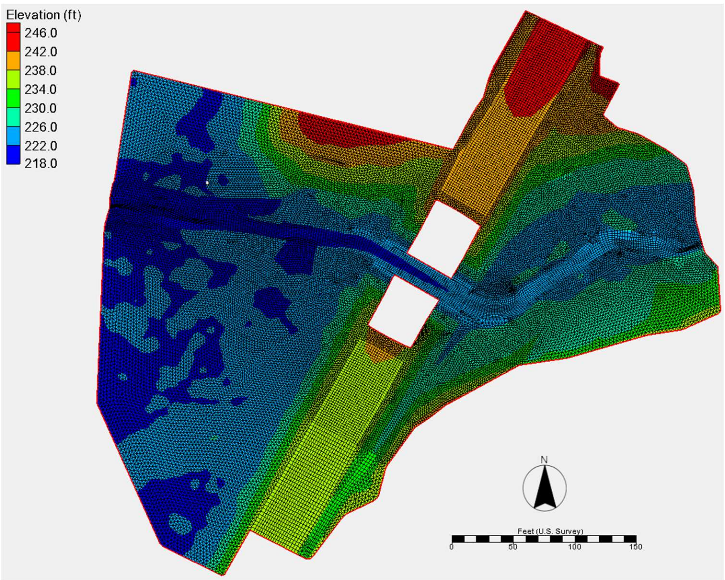

Figure 20: Proposed-conditions computational mesh with underlying terrain

4.1.3 *Materials/Roughness*

Manning’s n values were estimated for the natural channel and floodplain of the project stream using the Cowan method, based on site observations (Arcement and Schneider 1989; see Appendix G). The resulting values were consistent with standard engineering values for 1-D simulations (Barnes 1967). Because bank stabilizing vegetation is not expected to grow inside the structure, the channel there will have a dominant bed material composed of gravel and small cobble. The value for the culvert was estimated using the same reference, with a base value of n=0.035 for a gravel-cobble mix, and with 0.01 added to account for low profile bedforms that will be part of the final design (see Section 4.4). The resulting 1-D values were then adjusted down by 10 percent to reflect generally expected reductions when moving to a 2-D model parameterization (Robinson et al. 2019; Table 7). 21-23 depict the model spatial distributions of hydraulic roughness coefficient values for existing, natural, and proposed conditions, respectively.

Table 7: Manning’s n hydraulic roughness coefficient values used in the SRH-2D model

Land cover type	Manning’s n
Overbank	0.131
Channel	0.107
Road	0.020
Within Proposed Structure	0.041

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Figure 21: Spatial distributions of roughness values in existing-conditions SRH-2D model

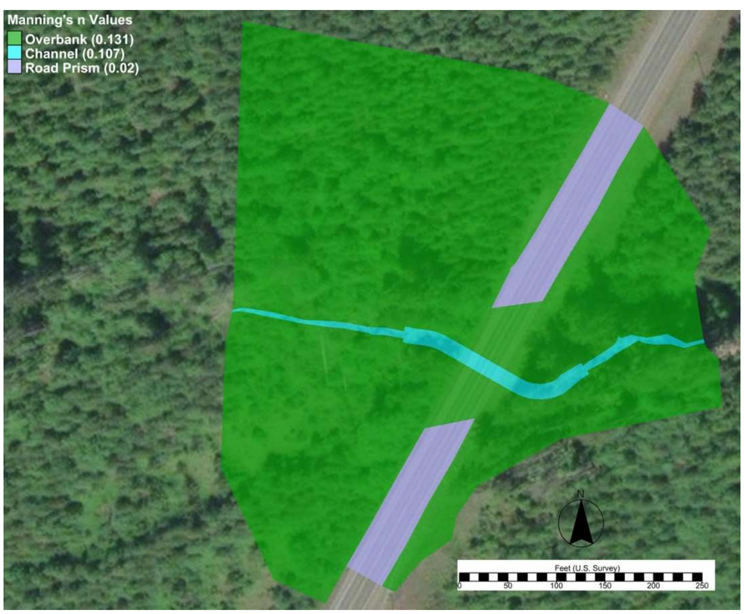

Figure 22: Spatial distributions of roughness values in natural-conditions SRH-2D model

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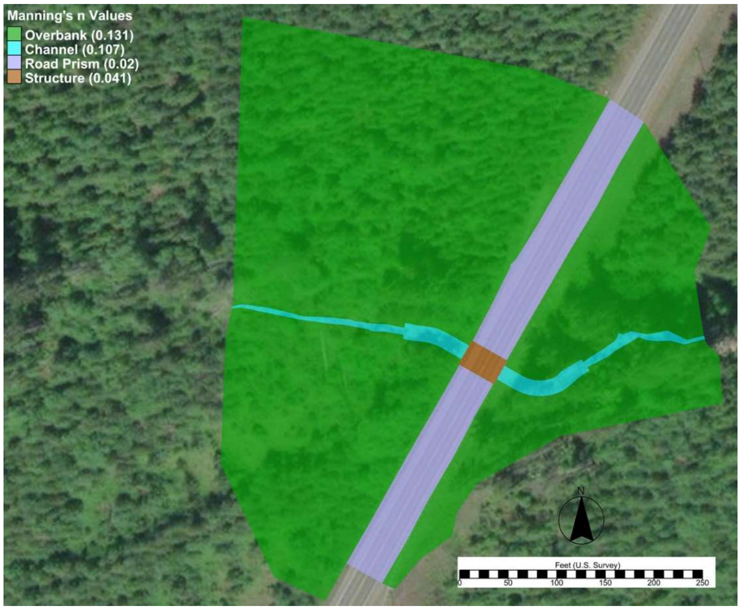

Figure 23: Spatial distributions of roughness values in proposed-conditions SRH-2D model

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4.1.4 *Boundary Conditions*

Model simulations were conducted using constant discharges including the 2-year, 100-year, 2080 projected 100-year, and 500-year flow events summarized in Section 3. External boundary conditions were applied at the upstream and the downstream boundaries of the model domain and remained the same between the existing-, natural- and the proposed-conditions model runs.

A constant flow rate was specified at the upstream boundary. Table 8 shows the simulated flow rate scenarios. Figure 24 shows the locations of external and internal boundaries in the existing-conditions model.

Normal depth rating curves were used to specify a flow dependent water surface elevation at the downstream boundary. The rating curve was developed within SMS using the existing terrain and the roughness data. For this calculation, the downstream slope was determined as 1.24 percent as measured from the terrain data. The composite roughness was calculated as 0.115. In addition, two LOB rating curves were developed because of flow in the floodplain. Figure 25 shows the normal depth rating curve for the main channel.

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An HY-8 internal boundary condition was specified in the existing-conditions model to represent the existing 87-foot-long circular CMP culvert crossing (Figure 26). The existing crossing was modeled as a 48-inch-diameter circular pipe within HY-8. A Manning's roughness of 0.024 was assigned to the culvert.

The culvert was assumed to be a straight pipe, with the inlet mitered to conform to the slope, and unobstructed and free from any stream material within the barrel Figure 23 shows a screenshot from the SMS Model with the input parameters for setting up the HY-8 culvert. For the natural conditions model, all boundary conditions are similar to that of the existing conditions model except there is no culvert in the natural conditions model (Figure 27).

The proposed structure was modeled by creating voids in the mesh to represent the locations of the abutments or walls. A symmetry (slip) boundary condition was specified in the proposed-conditions model to represent the longitudinal faces of the proposed structure (Figure 28). By default, SRH-2D uses a no-slip boundary at the boundaries, meaning that velocity is zero at the structure face. Using a slip boundary allows for velocity along the face of the structure for a more accurately representation.

Table 8: Flow rates for inlet boundary

Event	Flow Rate (ft³/sec)
2-year	38.6
100-year	97.3
2080 projected 100- year	116.2
500-year	119.0

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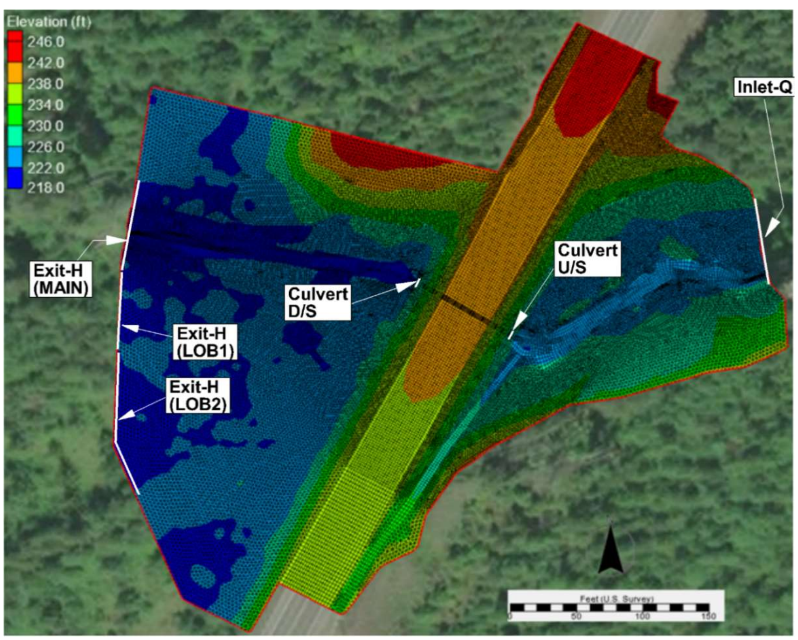

Figure 24: Locations of boundary conditions for the existing-conditions model

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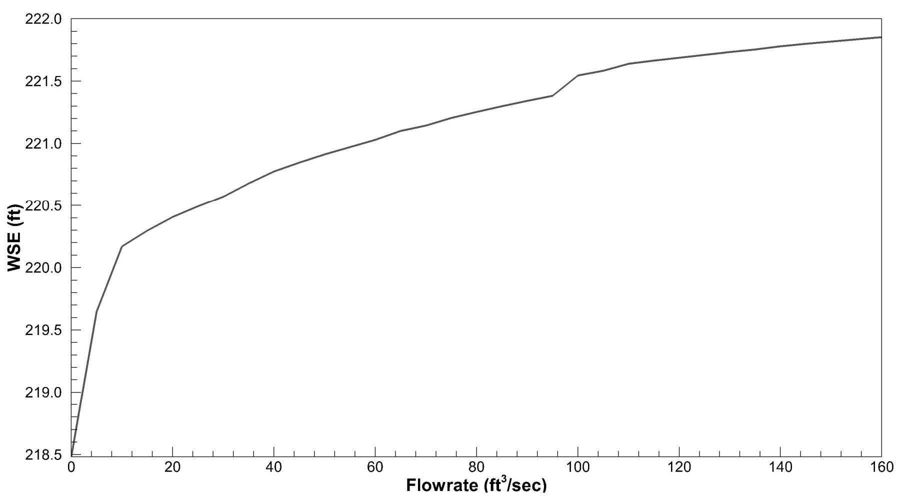

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Figure 25: Normal depth rating curve for downstream boundary (main channel)

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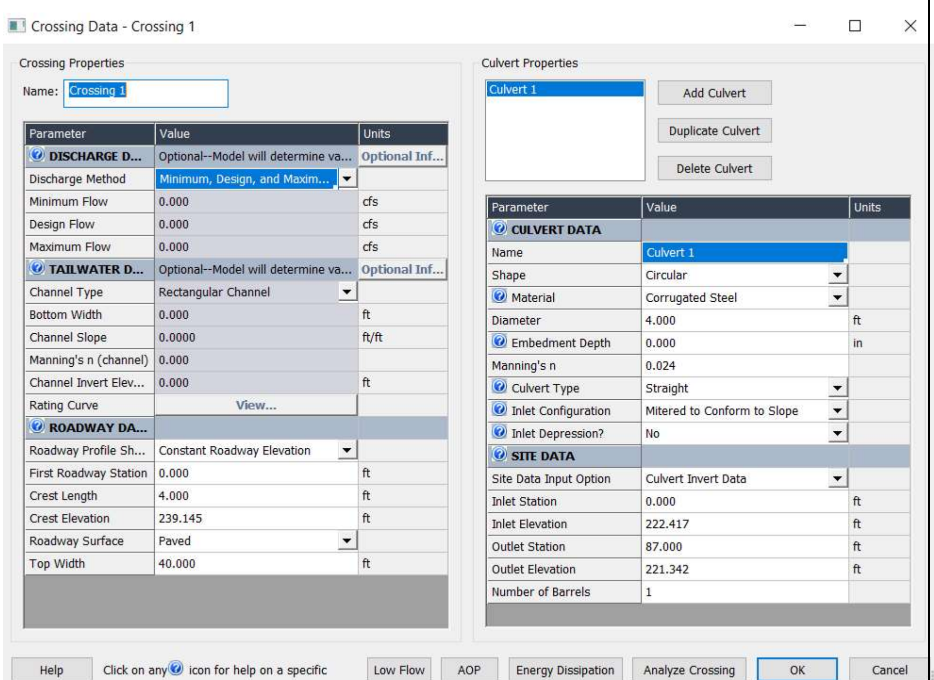

Figure 26: HY-8 culvert parameters

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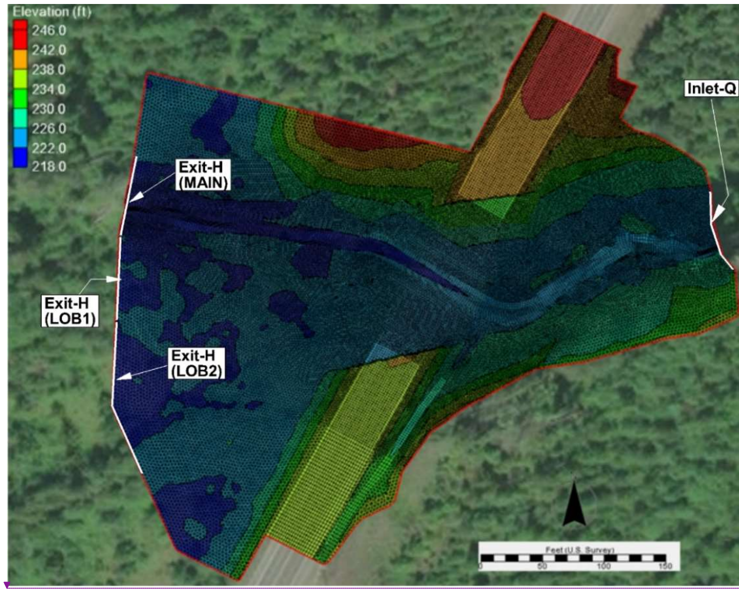

Figure 27: Location of boundary conditions for the natural-conditions model

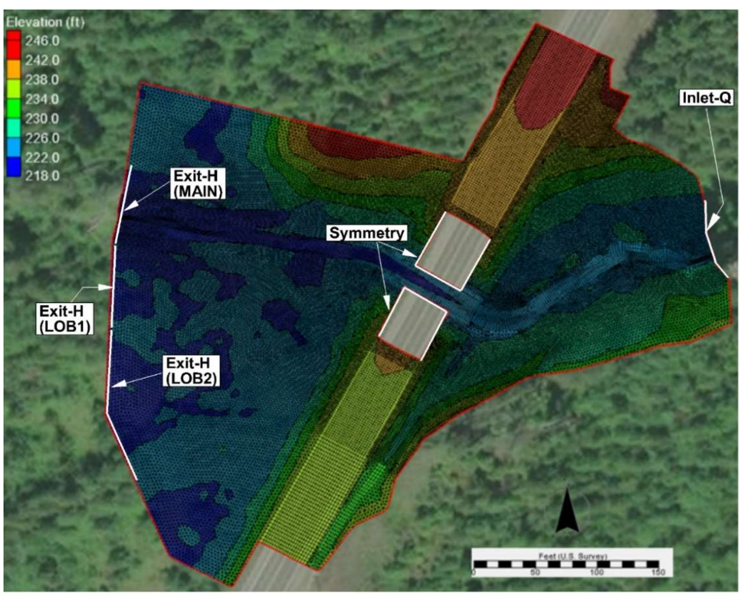

Figure 28: Location of boundary conditions for the proposed-conditions model

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4.1.5 *Model Run Controls*

Model controls were kept consistent between existing-, natural-, and proposed-conditions models. All model simulations were run for a sufficiently long duration until the results stabilized across the model domain. The following controls were set for the model runs:

- **Start time:** 0 hour
- **Time step:** 0.5 second
- **End time:** 4.0 hours
- **Initial condition:** dry

4.1.6 *Model Assumptions and Limitations*

The SRH-2D hydraulic model was developed to determine the minimum hydraulic structure opening, establish the proposed structure low chord elevation (and associated freeboard), and characterize hydraulic parameters used to design the crossing. There are several attributes of the data relied upon to develop the model that affect the resolution to which model output should be relied on. In particular, the survey data collected for developing the model terrain geometry were sufficient to capture macroscale variation in channel form and floodplain topography on the order of average channel width/depth/location and floodplain gradients. The spatial scatter of the survey point data was too coarse, however, to develop a model terrain capable of discerning an accurate and precise resolution of velocity distributions at smaller microtopographic scales, precluding predicting rapid spatial variation in hydraulic properties in association with bedform and instream roughness and flow obstruction variation. Accordingly, the designs are based on general, spatially averaged model predictions of velocity and shear stress, with an appropriate safety factor. Small scale variations in hydraulic properties should not be interpreted as signifying a meaningful feature of the design. Highly detailed design modeling of large wood structures is therefore not warranted, where structure stability and scour can be designed sufficiently using simply water depth and average channel values of velocity predicted by the model and increasing roughness locally.

In addition, the topographic extent of the area surveyed did not extend beyond the model predictions of inundation extent for the most extreme flood events, where the flooding extended onto areas of the adjoining surface generated from the LiDAR data. As seen in Figure 16, the LiDAR data appear to be biased high along the stream channel. This results in artificially concentrating flood flows onto the area within the bounds of the survey, and thus potentially over-predicting water surface elevations.

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The use of a steady peak inflow rate is an appropriate assumption to meet the model objectives. Using a constant inflow rate provides a conservative estimate of inundation extents and WSEL associated with a given peak flow, which is used to determine the structure size and low chord. Each simulation was run for a sufficient time to fill storage areas and for WSELs to stabilize until flow upstream equals flow downstream. During an actual runoff event, it is unlikely that the area upstream of the culvert would fill up entirely. This modeling method does not account for the attenuation of peak flows between the actual upstream and downstream hydrographs, with a large amount of storage upstream of the existing undersized culvert. An unsteady simulation could be used to route a hydrograph through the model to estimate peak flow attenuation for existing and proposed conditions. During an unsteady simulation, the

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areas upstream of the existing culvert would act as storage and as a result, the flow downstream of the crossing would likely be less than the current design peak flow event. Estimates of the downstream increases to WSEL and flow based on the constant inflow model results may then underestimate the change in downstream flood impacts. This is expected to be less of an issue for the natural conditions and proposed PHD scenarios at this site, however, where the channel size is small relative to the hydraulic opening, and the channel slope too steep, for flow attenuation effects to be significant.

The model results and recommendations in this report are based on the conditions of the project site and the associated watershed at the time of this study. Any modifications to the site, man-made or natural, could alter the analysis, findings, and recommendations contained herein and could invalidate the analysis, findings, and recommendations. Site conditions, completion of upstream or downstream projects, upstream or downstream land use changes, climate changes, vegetation changes, maintenance practice changes, or other factors may change over time. Additional analysis or updates may be required in the future because of these changes.

4.2 Existing-Conditions Model Results

Hydraulic results were summarized and compared at specific locations for the existing-conditions simulations. Seven cross sections (Figure 29) were selected to represent the model geometry on site: one at the roadway centerline, two in the selected reference reach upstream of the culvert, one immediately upstream of the culvert inlet, one immediately downstream of the culvert outlet, and two farther downstream. The cross sections just upstream and downstream of the culvert inlet and outlet show how the results change after installing the proposed structure. The reported hydraulic variables include maximum cross-sectional depth, cross-section averaged WSEL, velocity, and shear stress. Appendix C contains the detailed hydraulic results. In addition to the cross sections, results for existing, natural, and proposed conditions were summarized along the same longitudinal profile and stationing (Figure 30).

Table 9 summarizes the hydraulic results at seven cross sections for the project stream to Stevens Creek. Under existing conditions, the culvert is inlet controlled and causes backwater upstream of the inlet during all flow events simulated under U.S. 101 (Figure 31). Pressure flow in the existing culvert occurs for the 100-year flow event. The existing roadway was not overtopped within the range of flow events modeled for the proposed stream. A typical upstream section with WSELs is depicted in Figure 32. The maximum predicted velocities occur at the U.S. 101 culvert outlet (Figure 33).

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In the reaches upstream of the culvert backwater, average velocity ranges from 0.4 ft/s during the 500-year event to 1.2 1 ft/s at the 2-year event. In the downstream reaches, average channel velocities range from 0.9 ft/s during the 2 -year event to 2.3 5 ft/s during the 500-year event. Floodplain and main channel velocities are also summarized in Table 10. Average shear stress in the upstream reach ranges from 0 pounds per square foot (lb/ft²) during the 500-year event to 0.5 4 lb/ft² during the 2-year event. Shear stress values on the downstream are higher, ranging from 0.3 lb/ft² at the 2-year event to 2.2 1 lb/ft² during the 500-year event.

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Deleted: Figure 33**Error! Reference source not found.**). Upstream depths range from 2.5 feet during the 2-year event to 7.8 9 feet during the 500-year event. Depths in the downstream reach range from 2.01.9 feet at the 2-year event to 4.5 4 feet during the 500-year event....

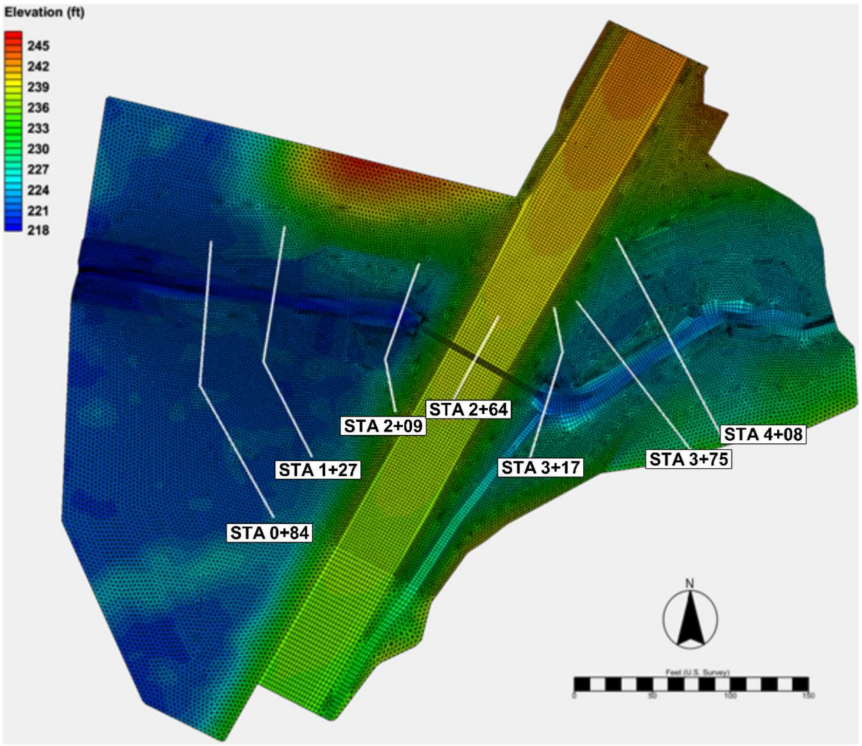

Figure 29: Locations of existing-conditions cross sections used for results reporting

Figure 30: Longitudinal profile stationing for existing, natural, and proposed conditions

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Table 9: Average hydraulic results for existing conditions

Hydraulic parameter	Cross section	2-year	100-year	2080 100-year	500-year
Average WSEL (ft)	DS 0+84	221.7	222.3	222.4	222.4
	DS 1+27	222.3	222.9	223	223.1
	DS 2+09	222.9	223.6	223.7	223.7
	Structure 2+64	NA	NA	NA	NA
	US 3+17	225.5	228	229.6	229.9
	US 3+75	225.6	228	229.6	229.9
	US 4+08	225.7	228.1	229.6	229.9
Max depth (ft)	DS 0+84	1.9	2.5	2.6	2.6
	DS 1+27	2.3	2.9	3	3.1
	DS 2+09	3.5	4.2	4.4	4.4
	Structure 2+64	NA	NA	NA	NA
	US 3+17	3.5	6	7.6	7.9
	US 3+75	3.2	5.6	7.2	7.5
	US 4+08	2.5	4.8	6.4	6.7
Average velocity (ft/s)	DS 0+84	1.8	2.4	2.5	2.5
	DS 1+27	1.7	2	2.1	2.1
	DS 2+09	0.9	2	2.4	2.4
	Structure 2+64	NA	NA	NA	NA
	US 3+17	0.6	0.9	0.9	0.9
	US 3+75	1.1	0.6	0.4	0.4
	US 4+08	1.1	0.6	0.4	0.4
Average shear (lb/ft^2)	DS 0+84	1.3	2	2.1	2.1
	DS 1+27	1	1.2	1.3	1.3
	DS 2+09	0.3	1.2	1.7	1.7
	Structure 2+64	NA	NA	NA	NA
	US 3+17	0.1	0.2	0.2	0.2
	US 3+75	0.3	0.1	0	0
	US 4+08	0.4	0.1	0	0

Table 10: Existing-conditions average channel and floodplains velocities at 100-year flood peak

Cross-section location	Q_{100} average velocities (ft/s)		
	LOB[a]	Main	ROB[a]
DS 0+84	0.4	2.4	0.9
DS 1+27	0.4	2.0	0.9
DS 2+09	0.6	2.0	0.5
Structure 2+64	NA	NA	NA
US 3+17	0.2	0.9	0.5
US 3+75	0.3	0.6	0.4
US 4+08	0.3	0.6	0.4

a. Properties of the LOB and ROB areas were calculated based on delineations established from the survey cross sections.

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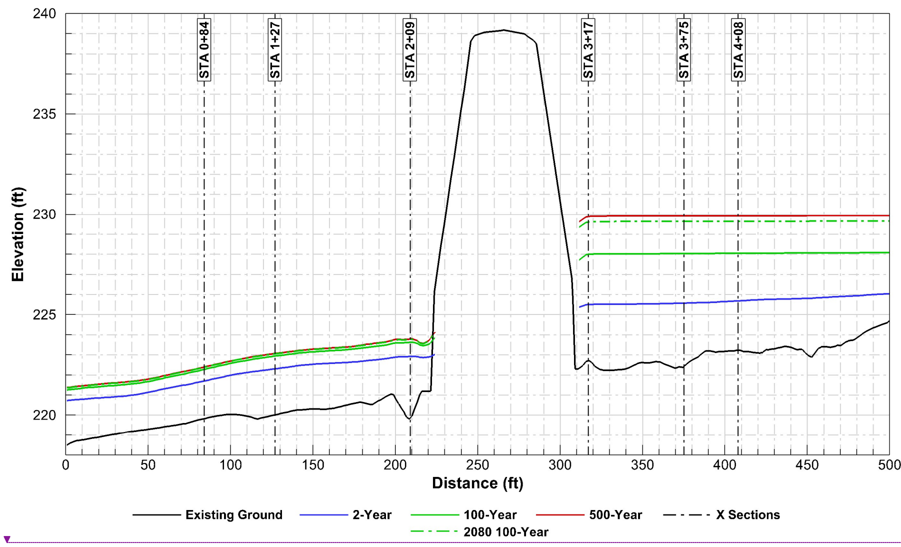

Figure 31: Existing-conditions water surface profiles

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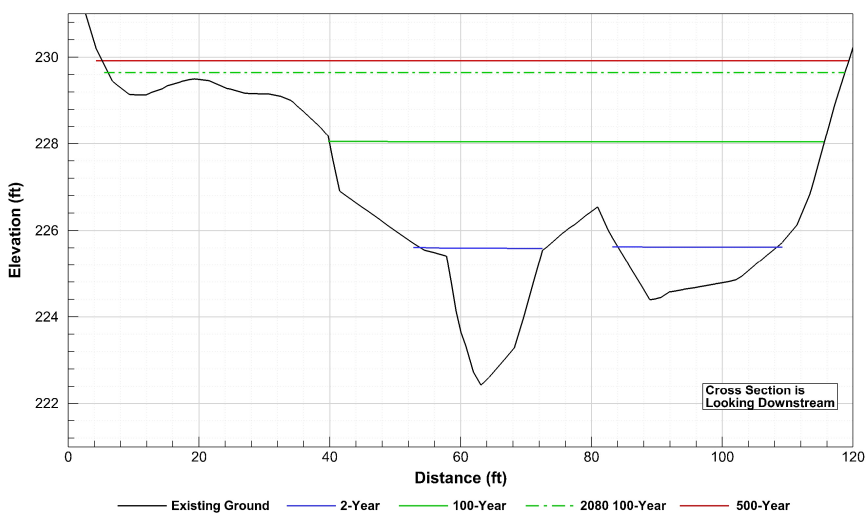

Figure 32: Typical upstream existing channel cross section (STA 3+75)

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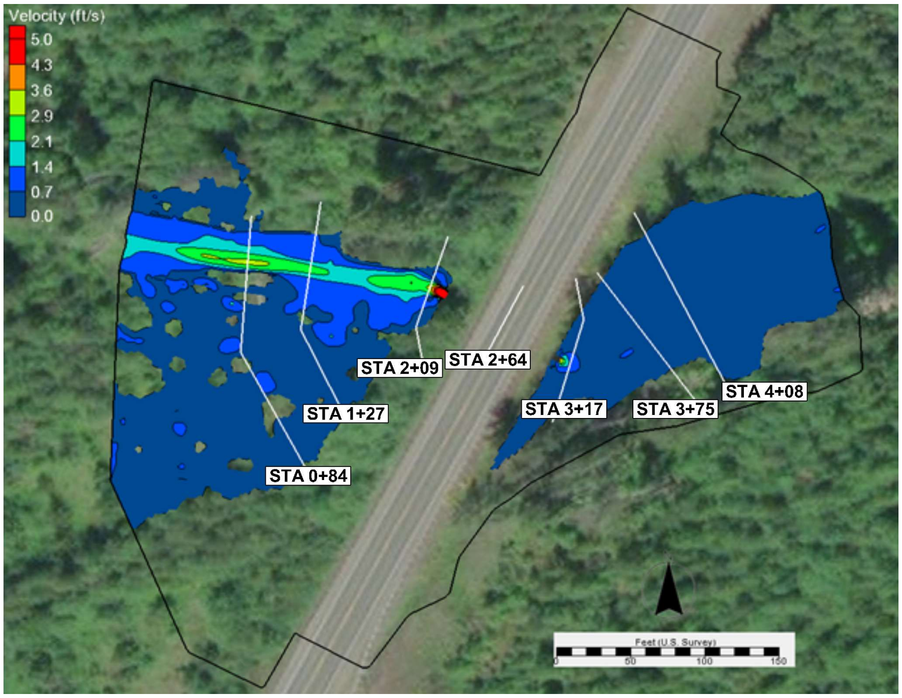

Figure 33: Existing-conditions 100-year velocity map with cross-section locations.

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4.3 Natural-Conditions Model Results

A natural-conditions model run was simulated to emulate a natural channel with roadway fill removed. The roadway was graded to allow the flow extents to follow the natural valley corridor without being obstructed by the road fill and existing culvert. Natural-conditions model cross-section locations are depicted in Figure 34. Natural-conditions hydraulic results for the main channel are summarized for the upstream and downstream cross sections as well as the cross section within the proposed crossing in Table 11. Average velocities across the main channel, LOB, and ROB of each cross section for the 100-year flow event are presented in Table 12.

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The WSELs for the range of flows simulated are depicted along the longitudinal profile in Figure 35. Under natural conditions, the crossing does not backwater or overtop U.S. 101. However, flow is still spread across the floodplain upstream and downstream because of low banks and flat floodplains. Typical cross sections for downstream and upstream are found in Figures 36 and 37, respectively. Both cross sections show an unconfined channel spreading flow into the floodplains at low flows. All cross sections are provided in Appendix C. Figure 38 depicts the predicted velocity map for the 100-year flood peak. Predicted upstream depths and velocities are similar to values downstream. The similarities in velocity reflect similar cross-section shapes and slopes, and flow spreading evenly across floodplains upstream, downstream, and through the removed road embankment.

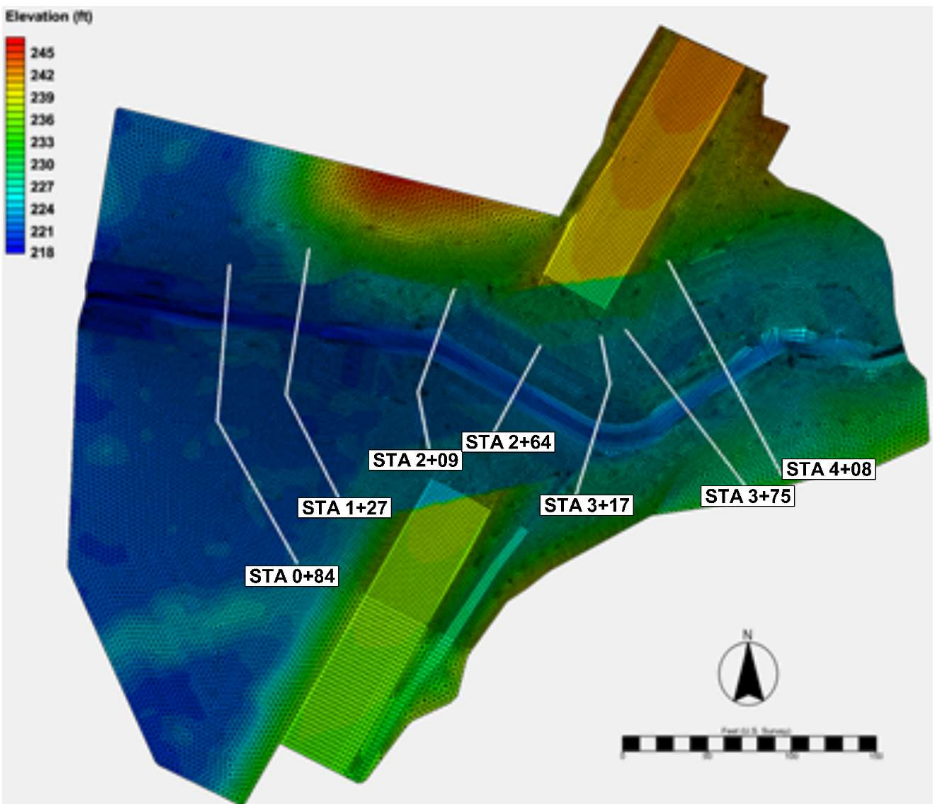

Figure 34: Locations of natural-conditions cross sections used for results reporting

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Table 11: Hydraulic results for natural conditions within main channel

Hydraulic parameter	Cross-section (STA)	2-year	100-year	2080 100-year	500-year
Average WSEL (ft)	XS 0+84	221.7	222.2	222.3	222.4
	XS 1+27	222.3	222.9	223.0	223.0
	XS 2+09	223.0	223.6	223.8	223.8
	XS 2+64[a]	223.6	224.3	224.4	224.4
	XS 3+17	224.2	224.9	225.0	225.0
	XS 3+75	224.8	225.5	225.7	225.7
	XS 4+08	225.3	226.0	226.2	226.2
Maximum water depth (ft)	XS 0+84	1.9	2.4	2.5	2.6
	XS 1+27	2.3	2.9	3.0	3.0
	XS 2+09	1.9	2.6	2.7	2.7
	XS 2+64[a]	2.0	2.6	2.8	2.8
	XS 3+17	2.0	2.6	2.8	2.8
	XS 3+75	2.4	3.1	3.3	3.3
	XS 4+08	2.1	2.8	3.0	3.0
Average velocity magnitude (ft/s)	XS 0+84	1.8	2.3	2.4	2.4
	XS 1+27	1.7	2.0	2.1	2.1
	XS 2+09	1.7	2.3	2.4	2.4
	XS 2+64[a]	1.6	2.3	2.4	2.4
	XS 3+17	1.4	1.9	2.1	2.1
	XS 3+75	1.7	2.5	2.6	2.7
	XS 4+08	1.5	2.1	2.2	2.2
Average shear stress (lb/ft^2)	XS 0+84	1.3	1.9	2.0	2.0
	XS 1+27	1.0	1.2	1.2	1.2
	XS 2+09	0.9	1.4	1.5	1.5
	XS 2+64[a]	0.9	1.4	1.5	1.5
	XS 3+17	0.7	1.1	1.2	1.2
	XS 3+75	0.9	1.6	1.7	1.7
	XS 4+08	0.8	1.3	1.4	1.4

a. Cross section located at removed roadway embankment.

Table 12: Natural-conditions velocities including floodplains at select cross sections

Location	Q100 average velocities (ft/s)		
	LOB [a]	Main	ROB [a]
XS 0+84	0.5	2.3	0.9
XS 1+27	0.4	2	0.9
XS 2+09	0.8	2.3	0.8
XS 2+64[b]	0.9	2.3	0.9
XS 3+17	0.7	1.9	0.9
XS 3+75	0.5	2.5	0.8
XS 4+08	0.5	2.1	0.9

a. a. Properties of the LOB and ROB areas were calculated based on delineations established from survey cross sections

b. Cross section located at removed roadway embankment.

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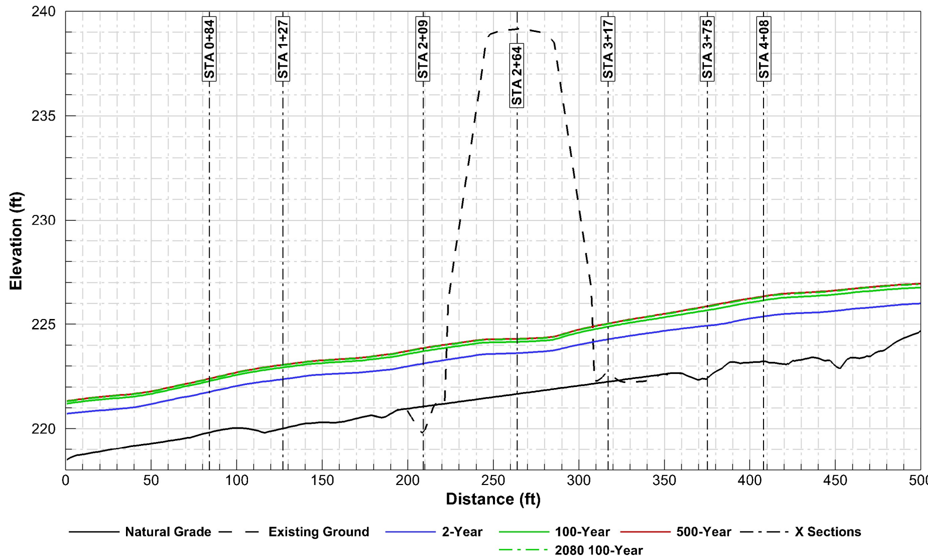

Figure 35: Natural-conditions water surface profiles

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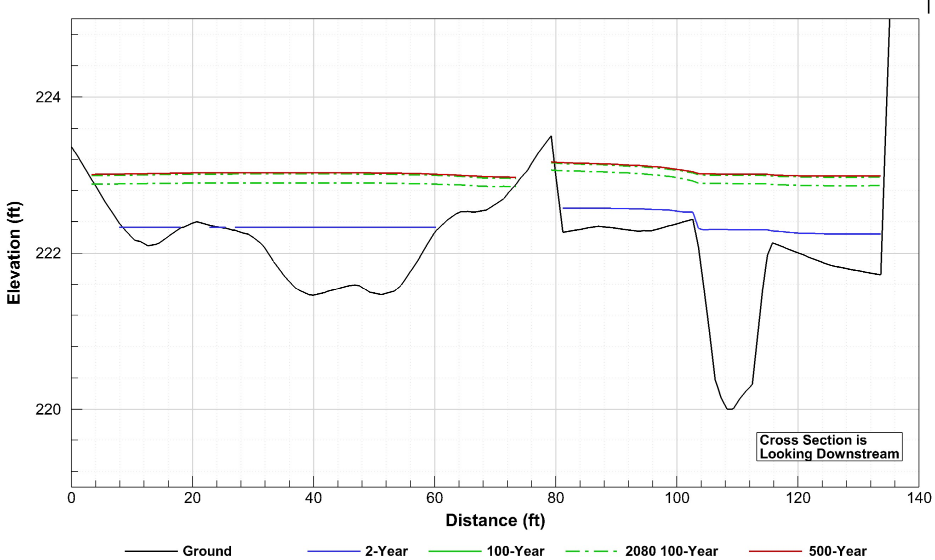

Figure 36: Typical downstream natural-conditions channel cross section (STA 1+27)

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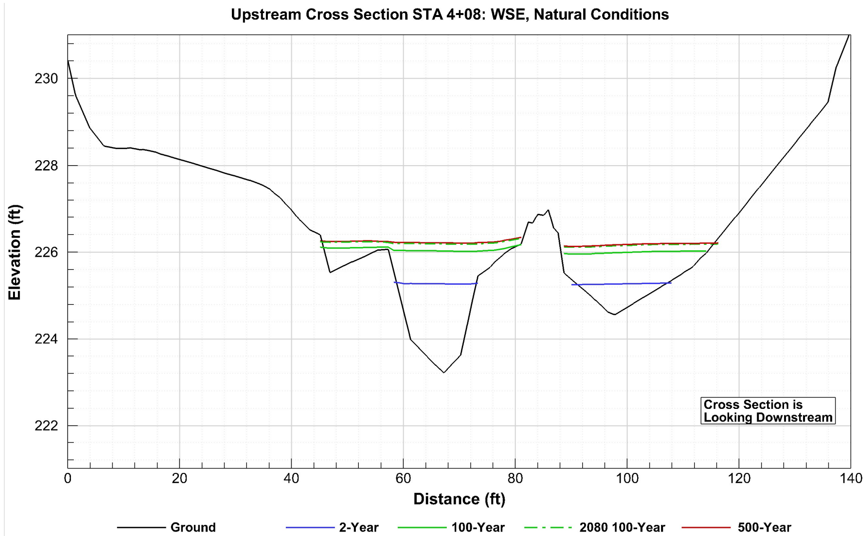

Figure 37: Typical upstream natural-conditions channel cross section (STA 4+08)

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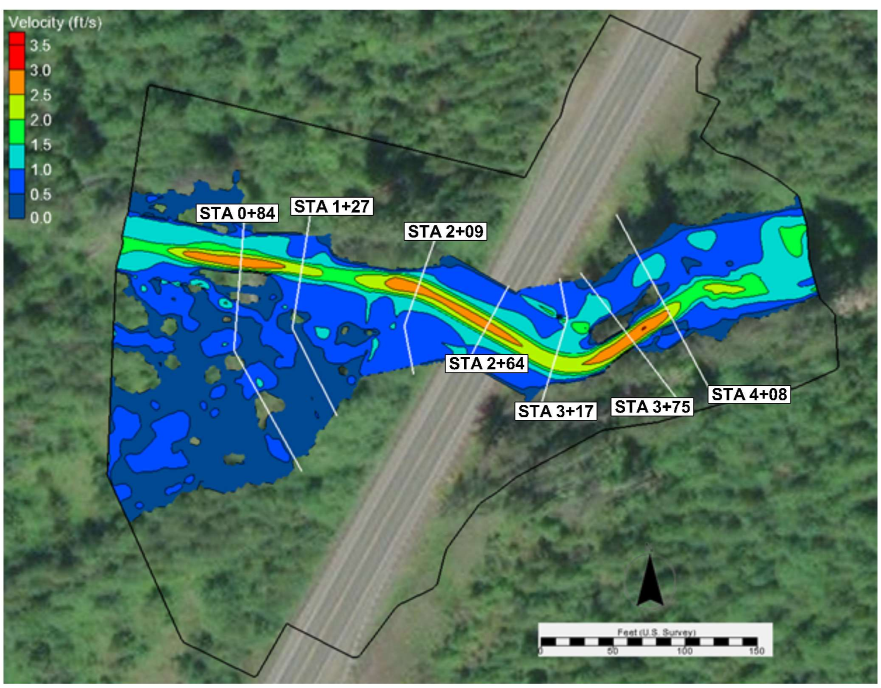

Figure 38: Natural-conditions 100-year velocity map with cross-section locations

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4.4 Channel Design

This section describes the development of the proposed channel cross-section and layout design.

4.4.1 *Floodplain Utilization Ratio*

The floodplain utilization ratio (FUR) is determined by dividing the flood-prone width (FPW) by the BFW. A ratio under 3.0 is considered a confined channel, and a ratio above 3.0 is considered an unconfined channel. The FPW was determined from the modeled 100-year event width for natural conditions at five cross sections. These values were each divided by the design BFW of 14.4 feet to compute the FUR. Table 13 shows each FPW, the calculated FUR, and the average FUR across all cross sections. The average result is a FUR of 7.6; therefore, the channel is designed as unconfined.

Table 13: FUR determination

Station	FPW (ft)	FUR
1+15	176	12
1+24	174	12
3+65	61	4.2
3+95	68	4.7
4+03	70	4.9
Average	110	7.6

4.4.2 *Channel Planform and Shape*

The WCDG prefers in a stream simulation design that the reconstructed channel planform and cross-section shape mimic conditions within a reference reach (Barnard et al. 2013). The proposed channel cross-section shape accordingly emulates WSDOT's typical reference channel-based design (Figure 39), with the relative location of the thalweg across the section varying depending on whether the channel is straight or curving. The bottom of the reference-based channel cross-section shape has a side slope of 10 horizontal (H):1 vertical (V) between the thalweg and bank toes, 2H:1V streambank slopes, and an overbank terrace at roughly a 50H:1V slope to create a channel similar to the observed existing channel shape. It is expected that the bottom shape will continue to adjust naturally during high water, where the proposed shape provides a reasonable starting point for subsequent channel shape evolution and bank stability will be provided via bioengineering design. Within the transition zone flanked by the road prism embankments, the same reference bankfull cross-section shape is maintained with steeper upper bank side slopes (Figure 40). The proposed design bankfull cross-section shape that concurrence was reached on is generally wider than the reference reach morphology (Figure 41). This helps slow down velocities within the replacement structure during the 100-year flood to offset effects of the lower channel roughness inside compared with the undisturbed channel.

A meandering planform is proposed within the replacement structure to increase total roughness within the culvert and accordingly reduce velocities, and to provide greater habitat complexity.

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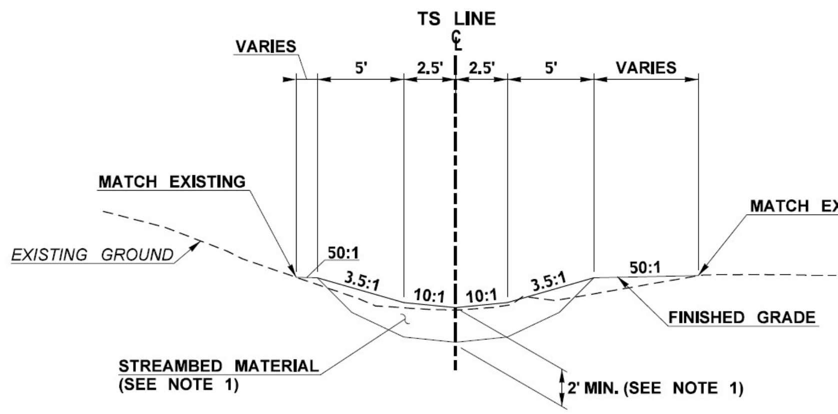

Figure 39: Design cross section outside of road embankment.

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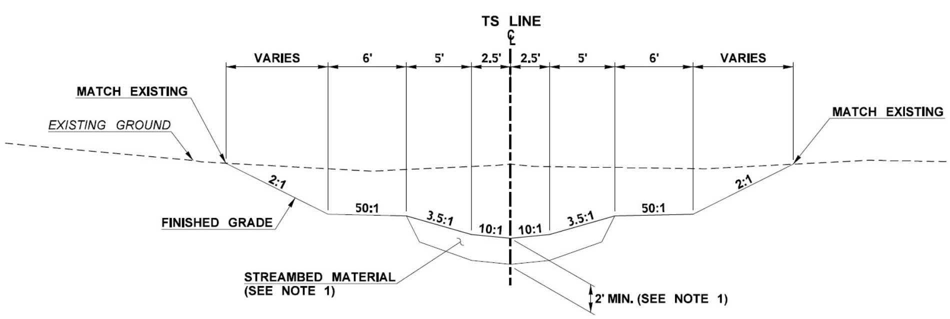

Figure 40: Design cross section within road embankment.

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Bioengineering methods can be implemented towards long term stability of the reference channel cross-section shape and planform outside the culvert. This is not necessarily applicable under replacement structures that are not long, high bridges, however, as is the case for this site where bank stabilizing vegetation typically will not grow and use of large woody material presents special constructability and maintenance problems. Except for very slow, low gradient channels, it is not possible to preserve a steep side slope without vegetation or specifying a particle size that is markedly larger than that typically specified in a stream simulation and is stable under all flows. For the project stream's gradient, the hydraulic modeling results and side slope stability equations predict that while the native gravel substrate GSD may be just stable on a 2H:1V side slope at the 2-year flood peak, it will be mobilized and the cross-section shape will regrade at higher flood levels (cf. Appendix D). Indeed, this is a primary reason why constructed stream simulation designs following a reference channel cross-section shape using gravel and cobble tend to wash out and flatten within the first winter season of high flows in many streams. However, as discussed in Section 5, the grain size distribution of the native substrate material is estimated to be sufficient to preclude complete flattening out of the streambed at this site. Constructed meander bars are accordingly also expected to remain stable.

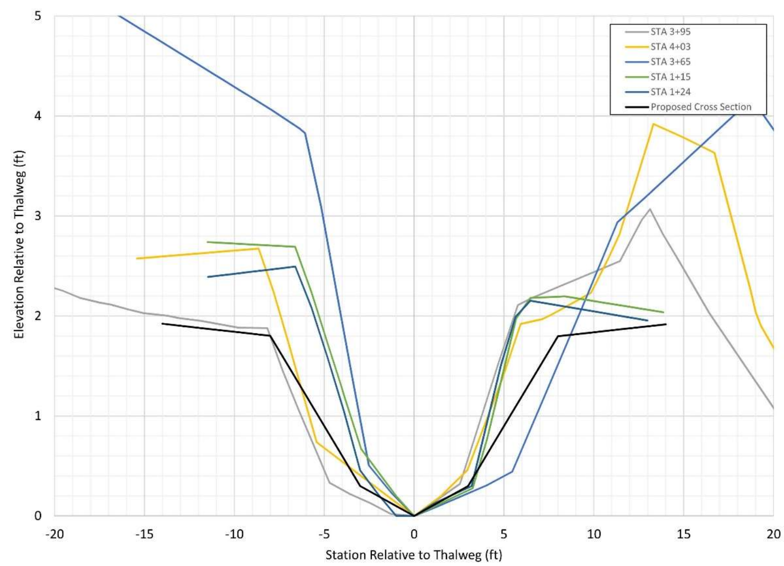

Figure 41: Proposed cross section at the structure superimposed with cross sections used to determine BFW

The design goal for spacing of the meander bars reflects a maximum head drop over a naturally formed riffle, rather than emulating a classic geomorphic pool-riffle spacing criterion, given the meander bars are intended to remain in place generally. To reduce the potential for re-grading to adversely affect upstream swimming ability, the head drop between bar centerlines (across the channel) should be below typical criteria for juvenile salmonids to accommodate upstream movements of other native fish species. For this site, a head drop of 3 inches between bar apices was selected based on professional judgment, where the drop is expected to be across a naturally formed riffle after the streambed is reworked by floods, assuming worst case regrading occurs such that the gradient of the streambed between bar apices becomes flatter.

4.4.3 *Channel Alignment*

The design channel will primarily follow the alignment of the existing stream and include channel regraded for approximately 155 feet, including tie-in distance. Upstream the proposed grading will tie into the existing channel approximately 36 feet upstream of the existing culvert inlet. Downstream the proposed grading ties into the existing channel 27 feet downstream of the existing culvert outlet.

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As can be inferred from above, there is some flexibility in the design of the cross-section profile side slope, but this reflects the constraint posed by substrate size. We have found a 7H:1V side slope to generally work well in that it is associated with a passage lane for juvenile salmonids that is approximately 2 inches deep at a flow of 1 cfs, and only a slightly greater D_{50} (1.25 inches) than the stable streambed mix for a flat slope (1.0 inches) is required for stability during the 100-year flood peak. This side slope is not substantially greater than the bottom slope of the reference-based streambed channel fill and thus can be warped to join the outside constructed channel cross-section. ¶
The prismatic option is simpler to construct than a meandering thalweg, but can be associated with faster flows because flow resistance is provided only by grain size. The meandering option can include an additive flow resistance component in the form of alternating bars that dissipate some of the stream energy as bedforms, and can be implemented via the following proposed design considerations:¶
The alternating bars should be composed of . . generally immobile material. Material between and around the bars can be composed of smaller grain sizes, albeit not so small that the intervening material is washed out without replacement. Based on calculations in section 5 and Appendix D, the bars will be composed of 4 inch minus cobbles, and the surrounding streambed will be composed of a mix of 4 inch cobble and streambed sediment following WSDOT's standard specifications 9-03.11(2) and 9-03.11(1), respectively.¶
Spacing of the bars should reflect a maximum head drop design goal rather than emulation of a classic geomorphic pool-riffle spacing criterion, given the bars are to be effectively stable. To reduce the potential for re-grading to adversely affect upstream swimming ability, the head drop between bar centerlines (across the channel) should be below typical criteria. For this site, a head drop of 3 inches was selected based on professional judgment. ¶
When the bar material is sized appropriately, the bars may deform somewhat, but as long as they stay in their general location to ensure that the head drop does not become excessive. ¶
The bar material should not protrude above the design surface, where the intervening material is designed to be in flush with the edge of the bar material and is sized to be stable on the prevailing stream gradient assuming negligible side slope.¶
A smaller opposing bar should be present to prevent entrainment along the culvert wall.¶
Additional boulders can be placed embedded into the streambed surface to provide additional energy dissipation and habitat.¶
The corresponding proposed design is depicted schematically in Figure 42....

The proposed channel alignment and grading extents are illustrated in design drawings provided in Appendix E.

4.4.4 Channel Gradient

The WCDG recommends that the proposed culvert bed gradient not be more than 25 percent steeper (slope ratio less than 1.25) than the existing stream gradient upstream of the crossing (WCDG Equation 3.1). The proposed channel gradient is 1.1 percent, and the average upstream and downstream channel gradients are approximately 1.1 percent, resulting in a slope ratio of 1.0 which satisfies WCDG recommendations. This project is anticipated to have a low risk for long-term degradation or aggradation and associated adjustment of gradient overall as discussed in Section 2.8.4.

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4.5 Design Methodology

The proposed fish passage design was developed using the 2013 *Water Crossing Design Guidelines* (Barnard et al. 2013) and the WSDOT *Hydraulics Manual* (WSDOT 2019). Using the guidance in these two documents, the unconfined bridge design methodology was determined to be the most appropriate starting point at this crossing because the FUR is greater than 3.0.

4.6 Future Conditions: Proposed 28-Foot Minimum Hydraulic Opening

The determination of the proposed minimum hydraulic opening width is described in section 4.7. A 28 feet wide opening was modeled as an open channel with a 14.4 feet BFW channel and floodplain, with vertical side walls. The resulting hydraulic predictions were used in the analyses described in section 4.4 to yield design parameters for freeboard and substrate sizing, and for guiding final design of a persistent cross-section profile within the culvert absent bank-stabilizing vegetation. Proposed-conditions hydraulic results are summarized in Table 14 for the upstream, within-structure, and downstream cross sections depicted in Figure 34. Average floodplain versus main channel velocities are summarized in Table 15. The predicted streamwise WSEL profiles are depicted in Figure 42 for the simulated floods. A typical section through the structure is depicted in Figure 43. Figures 44 and 45 depict predicted velocity maps for the present day and 2080 100-year flood peak flow scenarios. Under proposed conditions, the enlarged structure reduces the backwater upstream of the culvert throughout the regrading extents. The water surface elevation drops by roughly 4 feet from existing to proposed conditions at STA 3+17 upstream of the culvert inlet at the 100-year flood peak magnitude.

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Table 14: Average main channel hydraulic results for proposed conditions

Hydraulic parameter	Cross section	2-year	100-year	2080 100-year	500-year
Average WSEL (ft)	DS 0+84	221.7	222.3	222.4	222.4
	DS 1+27	222.3	222.9	223.1	223.1
	DS 2+09	223.0	223.7	223.8	223.8
	Structure 2+64	223.4	224.1	224.3	224.3
	US 3+17	224.1	224.8	225.0	225.0
	US 3+75	224.7	225.5	225.6	225.7
	US 4+08	225.3	226.0	226.2	226.2
Max depth (ft)	DS 0+84	1.9	2.5	2.6	2.6
	DS 1+27	2.3	2.9	3.1	3.1
	DS 2+09	1.9	2.6	2.7	2.7
	Structure 2+64	1.6	2.4	2.5	2.6
	US 3+17	1.8	2.5	2.7	2.7
	US 3+75	2.3	3.0	3.2	3.2
	US 4+08	2.0	2.8	3.0	3.0
Average velocity (ft/s)	DS 0+84	1.8	2.4	2.5	2.5
	DS 1+27	1.7	2.0	2.1	2.1
	DS 2+09	1.6	2.3	2.4	2.5
	Structure 2+64	2.0	2.6	2.8	2.8
	US 3+17	1.5	2.2	2.3	2.3
	US 3+75	1.8	2.6	2.8	2.8
	US 4+08	1.6	2.2	2.2	2.2
Average shear (lb/SF)	DS 0+84	1.3	2.0	2.1	2.1
	DS 1+27	1.0	1.2	1.3	1.3
	DS 2+09	0.8	1.4	1.5	1.6
	Structure 2+64	0.2	0.3	0.3	0.3
	US 3+17	0.5	1.0	1.1	1.1
	US 3+75	0.8	1.4	1.5	1.5
	US 4+08	1.0	1.8	2.0	2.0

Table 15: Proposed velocities including floodplains at select cross sections

Cross-section location	Q100 average velocities (ft/s)			2080 Q100 average velocities (ft/s)		
	LOB[a]	Main ch.	LOB[a]	LOB[a]	Main ch.	ROB[a]
DS 0+84	0.4	2.4	0.9	0.5	2.5	1.0
DS 1+27	0.4	2.0	0.9	0.5	2.1	1.0
DS 2+09	1.0	2.3	1.0	1.2	2.4	1.0
Structure 2+64	1.7	2.6	1.5	1.9	2.8	1.8
US 3+17	0.8	2.2	1.5	0.9	2.3	1.7
US 3+75	0.4	2.6	0.7	0.8	2.8	0.8
US 4+08	0.5	2.2	0.8	0.7	2.2	0.9

a. ROB/LOB locations determined from delineations based on survey cross sections.

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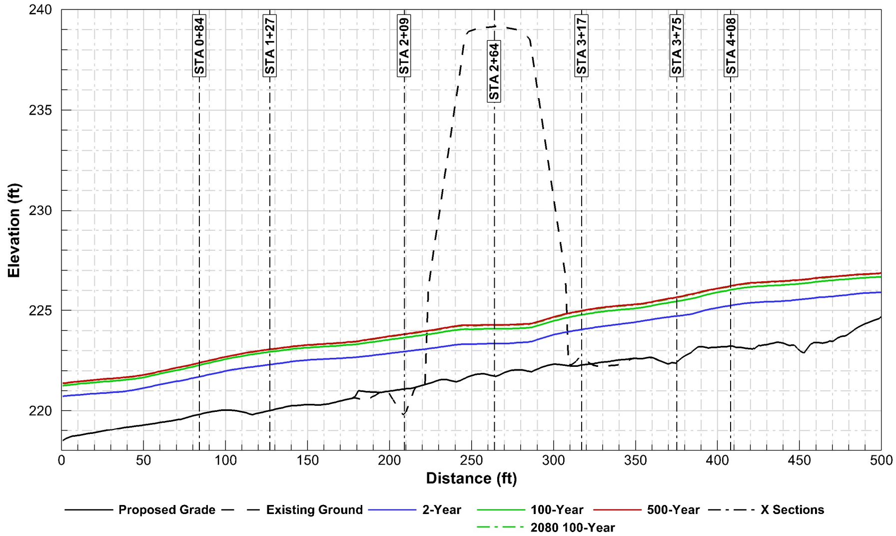

Figure 42: Proposed-conditions water surface profiles

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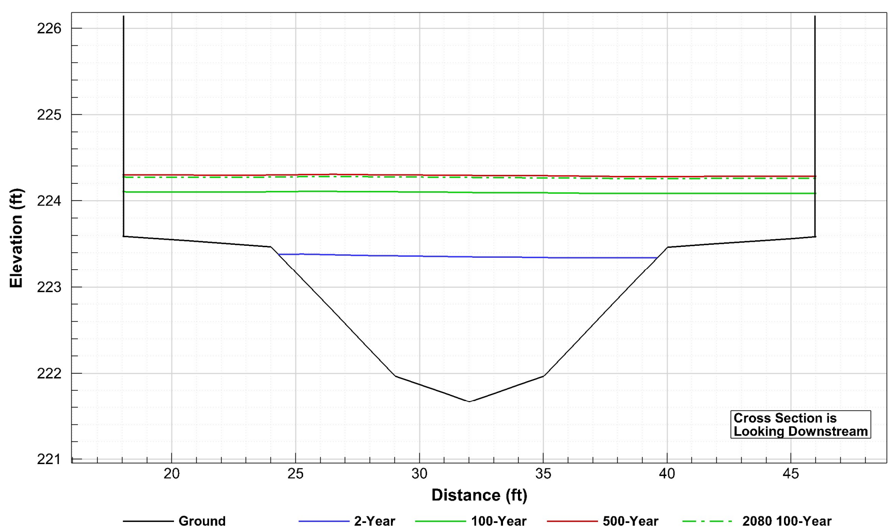

Figure 43: Typical section through proposed structure (STA 2+64)

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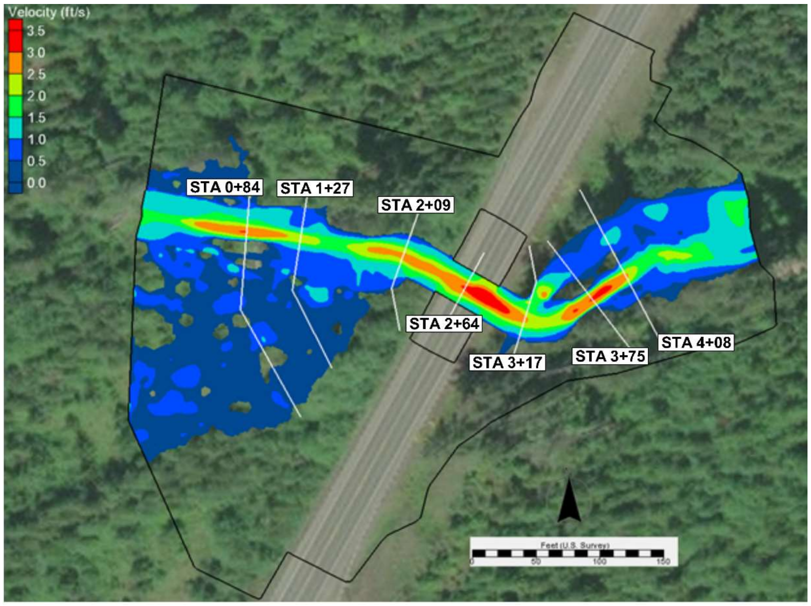

Figure 44: Proposed-conditions present day 100-year flood peak velocity map

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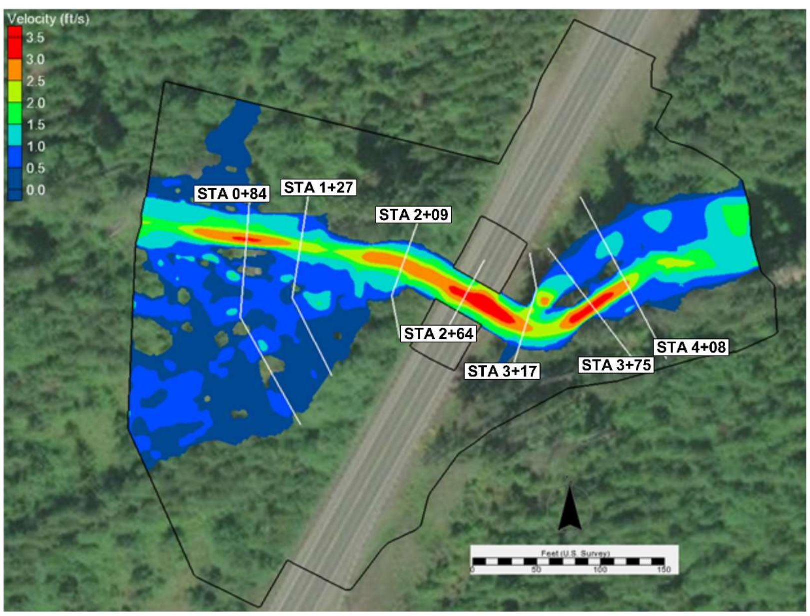

Figure 45: Proposed-conditions 2080 predicted 100-year flood peak velocity map

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4.7 Water Crossing Design

Water crossing design parameters include structure type, minimum hydraulic opening width and length, and freeboard requirements.

4.7.1 *Structure Type*

A structure type has not been resolved at present and will be determined at later project phases.

4.7.2 *Minimum Hydraulic Opening Width and Length*

The hydraulic opening is defined as the width perpendicular to the creek beneath the proposed structure necessary to convey the design flow and allow for natural geomorphic processes. The hydraulic opening assumes vertical walls at the edge of the hydraulic opening width unless otherwise specified. The starting point for the design of all WSDOT structures is Equation 3.2 of the WCDG, rounded up to the nearest whole foot. For this crossing, the minimum hydraulic opening value derived from Equation 3.2 was rounded up to 20 feet based on a bankfull width of 14.4 feet. During initial modeling performed in preparation of the draft PHD report, the structure size was increased iteratively until the calculated velocity ratio equaled 1.1 at both the 100-year and 2080 predicted 100-year events with a 28-feet wide hydraulic opening. However, that analysis was based on modeling that assumed the channel roughness inside the replacement structure was similar to outside. As discussed in Section 4.5, that assumption is unrealistic because roughness-providing vegetation cannot grow within the structure, large wood similarly will not be placed within the structure to trap more wood. Instead, the flow resistance inside the structure is expected to be substantially less than outside.

Accordingly, both 20 feet and 28 feet wide structures were simulated again as proposed conditions scenarios with updated roughness values. The present day and projected 2080 100-year flood magnitudes were evaluated for the proposed and reference conditions to evaluate the velocity ratio for both widths (Table 16). There was not a substantive difference in 100-year flood water surface elevations and thus velocities between the two widths (Figure 46). The results indicate that calculated velocity ratios are primarily an artifact of differences in channel roughness under the structure vs. outside, and of differences in relatively small velocity magnitudes. Given that it would not be physically possible to bring the velocity ratio down to a value of close to 1.1 without substantially widening the structure further, and that the velocities are relatively low, there is no functional advantage of a structure wider than 28 feet wide structure in terms of minimizing fish passage and geomorphic impacts.

Table 16: Summary of predicted present day 100-year channel velocities and velocity ratios for 20 and 28 feet wide structures

Structure width (ft)	Flow condition	Velocity – Proposed Condition (ft/s)	Velocity – Reference condition (ft/s)	Velocity ratio
28	100-year	2.6	2.1	1.2
	2080 100-year	2.8	2.2	1.3
20	100-year	2.8	2.1	1.3
	2080 100-year	3.1	2.2	1.4

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A structure length of approximately 41 feet fits within the existing road prism. This proposed length may be revised during development of the road and structure design.

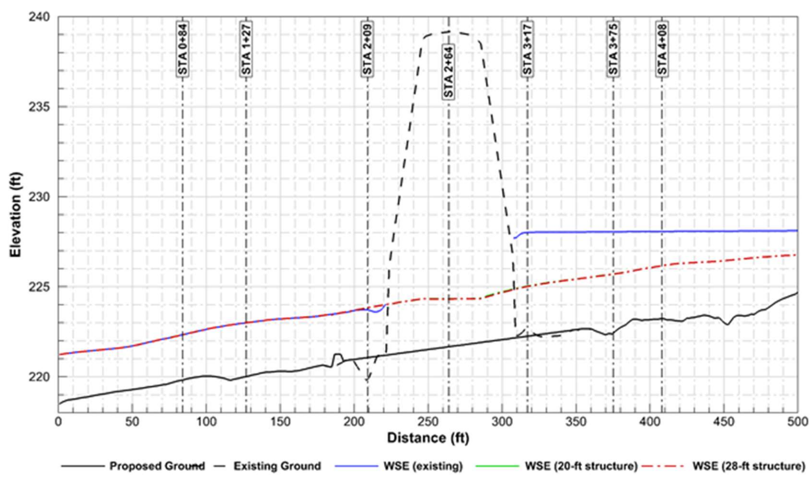

Figure 46: Existing and proposed 100-year water surface profile comparison for 20 feet and 28 feet wide structures

4.7.3 *Freeboard*

Freeboard is necessary to allow the free passage of debris expected to be encountered. The WCDG generally suggests a minimum 3-feet clearance above the 100-year WSEL for streams with a BFW greater than 15 feet to adequately pass debris (Barnard et al. 2013). WSDOT also desires a minimum vertical clearance between the culvert soffit and the streambed thalweg for maintenance equal to 6 feet where possible. WSDOT is incorporating climate resilience in freeboard, where practicable, and so freeboard was evaluated at the projected 2080 100-year WSEL. The hydraulic modeling indicates that the maintenance-based goal will exceed the clearance required to meet the 3 feet hydraulic-based criterion associated with the proposed design when constructed. The resulting parameters governing freeboard are summarized in Table 17.

Table 17: Low chord determination results

Parameter	2080 100-Year Flood Predictions	
	At Inlet	At Outlet
Thalweg elevation (ft)	222.20	221.20
Maximum WSEL (ft)	224.90	223.9
Minimum low chord elevation to provide 3 feet of freeboard (ft)	227.90	226.9
Minimum low chord elevation to provide 6 feet maintenance access (ft)	228.20	227.20
Recommended low chord elevation, without future aggradation (ft)	228.20	227.20

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Moved up [1]: A structure length of approximately 41 feet fits within the existing road prism. This proposed length may be fine-tuned during development of the road and structure design.

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4.7.3.1 *Past Maintenance Records*

WSDOT has indicated there have been no maintenance problems at this crossing.

4.7.3.2 *Wood and Sediment Supply*

The project stream flows through a heavily wooded basin with a high potential for recruitment. The lower gradient wetlands upstream of the crossing are likely to trap any large mobile wood, however. As described in section 2.8.6, mobile wood pieces in the stream appear to be smaller than 10 inches in diameter and around 16 feet in length, and thus would be expected to clear easily under the proposed 28 feet wide structure with more than 3 feet of freeboard during the 100-year flood now and in the future. The evaluation of long-term aggradation and degradation presented in Section 2.8.4 indicated that there is a low likelihood of aggradation at the site, where additional freeboard to accommodate future aggradation does not appear warranted at this site.

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4.7.3.3 *Flooding*

Flooding history is unknown for this site and no WSDOT maintenance records were received related to roadway overtopping or flooding. The model results show a rise just downstream of the culvert because of grading impacts, but farther downstream the WSELs do not change. The proposed structure will reduce backwater and the water surface will be lowered upstream.

4.7.3.4 *Future Corridor Plans*

There are currently no known long-term plans to improve U.S. 101 through this site.

5 Streambed Design

The streambed design considered the local characteristic grain size distribution (GSD) of gravel measured in the pebble count, standard streambed stability calculations for the proposed channel longitudinal and cross-section profile grading, and requirements of WAC 220-660-190. Two GSDs will be proposed for this site. One grain size distribution is for the streambed mix, which is presented in the section below, and the second is for proposed meander bars within the replacement structure. Partial channel-spanning meander bars are recommended within the proposed structure to encourage natural channel evolution and flow complexity within the constructed channel. The gradation for the proposed meander bars will be designed during the FHD phase. In addition, large woody material is proposed to be placed on and over the streambed to provide instream habitat complexity and overhead cover for fish. These two elements of the design are described in separate sections below.

5.1 Bed Material

Where neither of the other two alternative approaches identified in Section 1.0 are indicated for implementation, the injunction requires that the design follow the unconfined bridge design methodology as described in the WAC and WCDG (Barnard et al. 2013). WAC 220-660-190 stipulates that "The median particle size of sediment placed inside the stream-simulation culvert must be approximately twenty percent of the median particle size found in a reference reach of the same stream. The department [WDFW] may approve exceptions if the proposed alternative sediment is appropriate for the circumstances."

For sediment sizing, WSDOT uses the Modified Critical Shear Stress Approach, as described in Appendix E of the 2008 US Forest Service (USFS) Guidelines for all systems under 4 percent and the Unit-Discharge Bed Design as described by the 2013 WCDG for systems greater than 4 percent. Since the grade of the unnamed tributary to Stevens Creek near the US 101 crossing is less than 4 percent, the proposed streambed gradation for the new channel was sized using the Modified Shield's Critical Shear Stress Approach. The mobility analysis performed on the design gradation detailed below uses the 100-year peak flow as the design flow.

The reference reach of this stream is primarily composed of fines, with some isolated gravel patches. The streambed material through the reference reach was documented with a pebble count during a site visit on July 13, 2021 and is discussed in Section 2.8.3. The proposed gradation for the unnamed tributary to Stevens Creek is designed to be more consistent with the native gravel patches, and will be 100 percent of Standard Specification 9-03.11(1) Streambed Sediment. Calculations based on the Modified Shields stress method indicate that every particle size will remain immobile during all storm events due to the low average modeled shear stresses in the proposed channel. The geomorphic reach conditions are such that the supply rate of native gravel from upstream would be insufficient to replace gravel mobilized form the culvert streambed over the long term. Therefore, the largely immobile proposed streambed design consisting of 100% streambed sediment is appropriate for this site. A summary of the observed and proposed gradations is presented in Table 18, where the proposed GSD reflects the stable D_{84} size and using WSDOT's standard specification 9-03.11(1). WSDOT's worksheet

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Deleted: WSDOT has decided that exceptions should be avoided where possible. In general, what this means is that the streambed substrate grain size distribution is required to have a D_{50} within +/- 20 percent of the native reference substrate. This requirement is not strictly possible to meet at this site, because the reference reach substrate consists primarily of fine material that would not be expected to remain stable if placed within the culvert. There are isolated patches of gravel, so an exception is recommended for this site where the streambed design is instead based on the reference gravel patch grain size distribution with an assessment of risks associated with potential streambed instability. Relevant calculations are presented in Appendix D and their implications to the design are summarized below.

calculations for the proposed streambed mix are presented in Appendix D. As previously mentioned, the proposed meander bar gradation will be included with the final hydraulic design.

Table 18: Comparison of observed and proposed streambed materials

Sediment size	Observed diameter (in)	Proposed Minimum Streambed Design Diameter (in)
D_{16}	0.4	0.1
D_{50}	0.8	0.6
D_{84}	1.4	1.7
D_{90}	1.5	1.9
D_{MAX}	2.4	2.5

5.2 Channel Complexity

To mimic the natural riverine environment and promote the formation of habitat, the design incorporated placement of key LWM pieces within and across the channel and floodplain. Placement will generally mimic tree fall that is common throughout the reach upstream and downstream of the crossing. Complexity is also provided by the alternating bar layout proposed in Section 4.4.

5.2.1 *Design Concept*

The total number of key pieces was determined in consideration of criteria presented in Fox and Bolton (2007) and Chapter 10 of the *Hydraulics Manual* (WSDOT 2019), in which WSDOT's recommended key piece density for the project site is 3.4 key pieces and 39.48 cubic yards of volume per 100 feet of channel. A key piece is defined as having a minimum volume of 1.31 cubic yards, which corresponds roughly to a 30 feet long log that has a diameter at breast height (DBH) of 15 inches. WSDOT has established a design goal for this project where the Fox and Bolton (2007) criteria are to be calculated for the total regrade reach length including the culvert, but the pieces of wood are to distribute outside of the culvert. For the proposed total regrade length of 156 feet, the design criteria for this reach are five key pieces with a total volume of 61.6 cubic yards (Appendix H). In small streams, the volume criterion may not always be practically achieved without completely filling the channel and placing a sizeable amount of wood outside of the 2 year flood extent, where smaller diameter logs can achieve the same biological and geomorphic functions. In this design, the primary goal was to exceed the density criterion to get closer to or even meet the volume criterion, while not overloading the stream channel outside of the culvert. Where feasible, wood can be added outside of the regrade extent with the condition that heavy equipment not disturb the channel and floodplain significantly.

A conceptual LWM layout has been developed for the project reach involving placement of loose logs with rootwads (Figure 47). The conceptual layout proposes twelve key pieces in a 156-foot-long project reach (including the structure length), which exceeds the number criterion. It does not appear to be scale appropriate at this site to place additional wood to meet the volume target, which would require much larger pieces of wood packed into a small area. Pieces are arranged in a way that mimics existing large wood orientations upstream and downstream of the crossing. There is space for this number of

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The SRH-2D model outputs an estimate of shear stress, but the result is based on a 2-D vector adaptation of the uniform flow, wide channel 1-D approximation, and accordingly is a significant over-estimate compared with that derived from velocity profiles (Wilcock 1996; Pasternack et al. 2006; DeVries et al. 2014). Pasternack and Brown (2013) determined that the type of equation used more closely matches the velocity profile-derived estimate when the velocity is evaluated near the bed. However, SRH-2D calculates a mean column velocity, but that can be used to estimate near bed shear velocity and thus shear stress. Two different velocity relations based on the rough form of the law of the wall were evaluated accordingly, and they gave comparable order of magnitude predictions of shear stress (Richards 1982; Pasternack and Brown 2013). The larger of the two estimates was used to size streambed substrates accordingly using Shields' equation (see Appendix D). For specifying the overall grain size distribution, guidelines were adopted from Barnard et al. (2013) and USACE (1994). ¶
Following the above approach, the critical Shields stress = 0.045 criterion corresponds approximately to a critical D_{50} = 0.2 inches at both the 2-year and 2080 100-year flood peaks. Correspondingly, a streambed mix emulating the native gravel GSD in Table 4 with a D_{50} = 0.8 inches would be expected to be stable at both the 2-year and 100-year flood peaks. The modified Shields approach (USFS 2008) similarly predicts that the native gravel D_{84} size should be generally stable. This result is consistent with field observations inferring general stability of isolated gravel deposits in the ... [12]

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pieces, and can utilize pieces of wood in the 15- to 24-inch DBH range, sizes that are comparable to other pieces of wood at the site and give the contractor flexibility in sourcing wood. This increased number of variable sized pieces in turn facilitates getting closer to the net volume target. The mobility and stabilization of LWM will be analyzed in later phases of design. The design involves placing loose, 30+ feet long logs with rootwads, and to the extent possible, with intact branches. Two will be placed entirely in the channel (Type 2), eight will be placed with rootwad in the channel and tip on the floodplain/adjacent slope (Type 3), and two will span the bankfull channel to promote scouring underneath (Type 4). The type 3 and 4 designs will involve self-ballasting and interlocking with existing trees for stability. The type 2 log will be kept in place by other logs on top, and wedging between streambanks.

The LWM pieces will be placed so they provide cover habitat for juvenile salmonids during winter months, including refuge habitat under high flow conditions. Wood stability and the need for anchoring will be assessed at the Final Hydraulic Design (FHD) level. Key pieces will be designed to be anchored by either suitable embedment length/depth, or interlocking with existing trees. To meet WSDOT's total LWM number target, six (6) additional 12" or larger DBH trees with rootwads would be needed. These smaller pieces would need to be placed loose as directed work and integrated with the installation of key pieces.

Risk of fish stranding is possible in scour pools around rootwads because the stream was observed to go dry during the summer of 2021. Accordingly, scour pool excavation around rootwads is not included in the design for this site. A large, deep pool would need to be constructed to emulate the pool at the logging road crossing upstream where small-bodied salmonids were observed over the summer of 2021. However, given the proximity of the crossing to a convex slope break that could promote lowering of the water table locally upstream, it cannot be assumed that the pool would stay watered during the summer. A more detailed field sampling program involving piezometers is recommended to evaluate this possibility if pool formation is a goal at this crossing.

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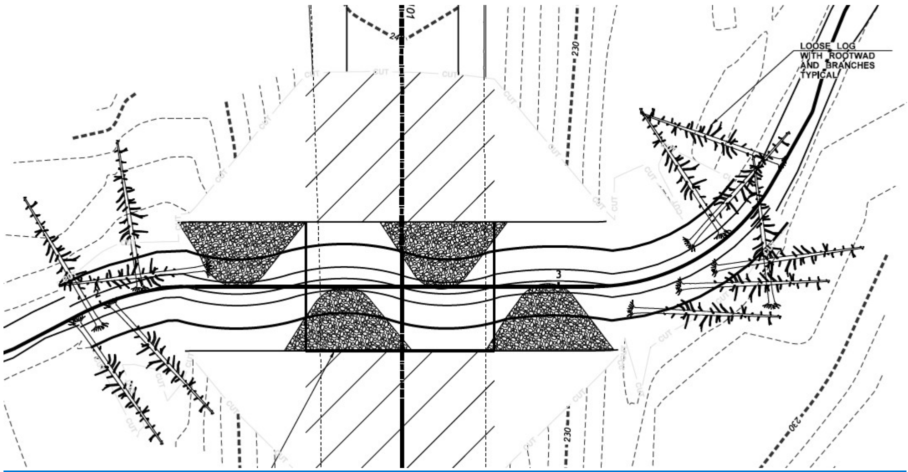

Figure 47: Conceptual layout of habitat complexity features

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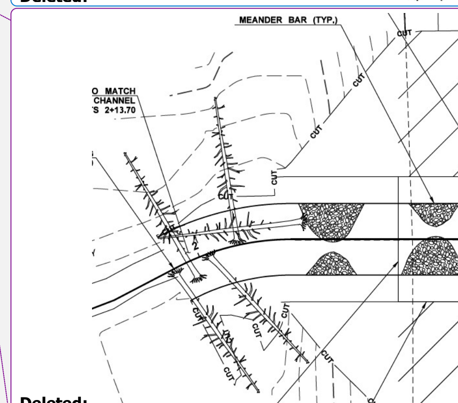
Deleted: 

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6 Floodplain Changes

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This project is within a mapped floodplain. The pre-project and expected post-project conditions were evaluated to determine whether there would be a change in WSEL and floodplain storage.

6.1 Floodplain Storage

Floodplain storage is anticipated to be affected by the proposed structure. The installation of a larger hydraulic opening will greatly reduce the amount of backwater and associated peak flow attenuation that was being caused by the smaller existing culvert. A comparison of pre- and post-project peak flow events was not quantified as the models were run with a steady flow rate specified at the upstream boundary of the model. No infrastructure was observed downstream of the project site in the proposed stream to Stevens Creek, that would be affected by the reduction in flow attenuation upstream of the proposed crossing.

6.2 Water Surface Elevations

Installation of the proposed structure would eliminate the backwater impacts immediately upstream of the existing culvert, resulting in a reduction in WSEL upstream. The WSEL is reduced by as much as 3.0 feet near the inlet of the existing culvert at the 100-year event as shown in Figure 48. Figure 49 depicts the extent of backwater that will be eliminated. At the culvert outlet the proposed grading increases the WSEL by up to 0.4 feet. Twenty feet past the culvert outlet, there is no change in WSEL (Figure 49).

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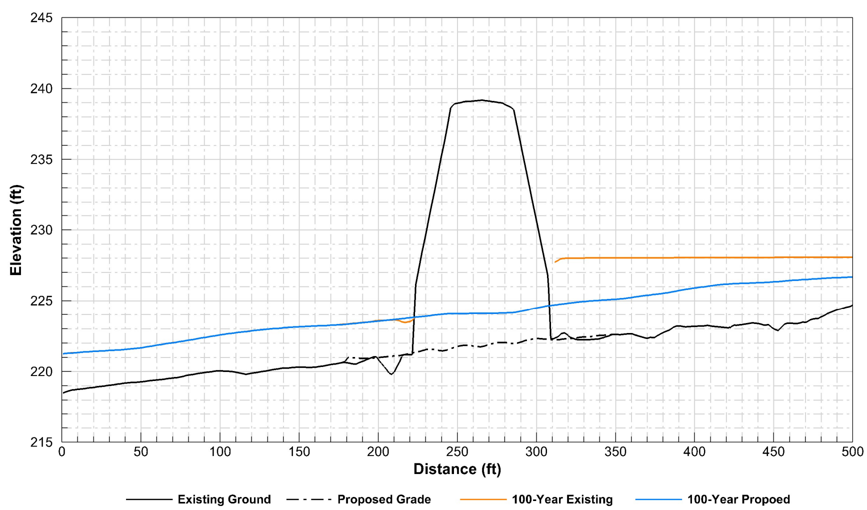

Figure 48: Existing and proposed 100-year water surface profile comparison

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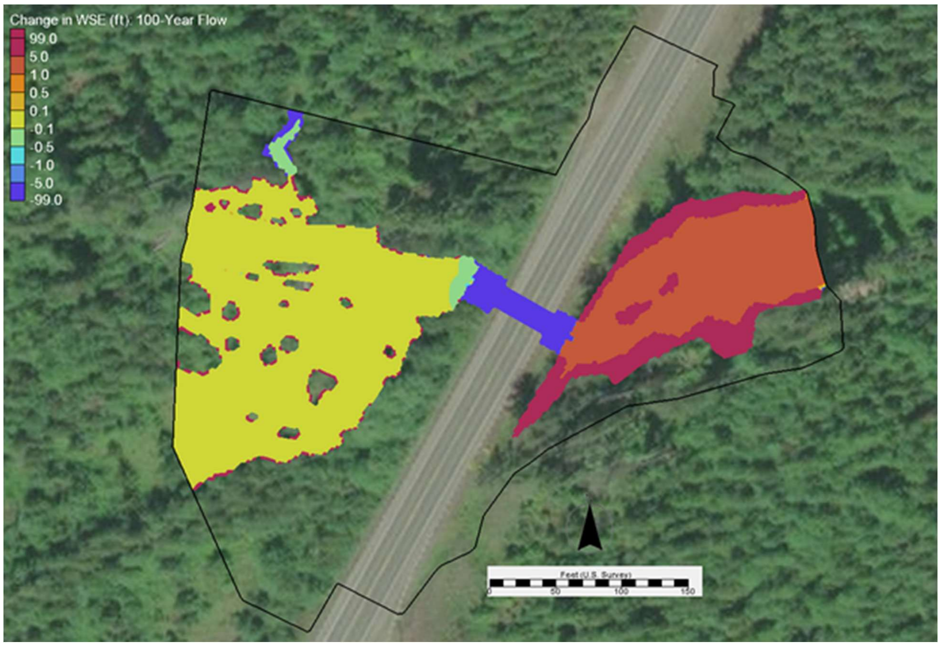

Figure 49: Map of water surface elevation changes (existing minus proposed) with a replacement structure

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7 Climate Resilience

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WSDOT recognizes climate resilience as a component of the integrity of its structures and approaches the design of bridges and buried structures through a risk-based assessment. For bridges and buried structures, the largest risk to the structures will come from increases in flow. The goal of fish passage projects is to maintain natural channel processes through the life of the structure and maintain passability for all expected life stages and species in a system. At a minimum, climate change is addressed in all bridge, buried structure, and fish passage projects by providing a design in which the foundations or bottoms are not exposed during the 500-year flow event due to long-term degradation or scour. WSDOT also completes a hydraulic model for all water crossings on fish-bearing streams, regardless of design methodology, to ensure that the new structure is appropriately sized. If the velocities through the structure differ greatly from those found elsewhere in the reach, the structure width may be increased above what is required by Equation 3.2 in the WCDG.

General climate change predictions for the broader region are for increased rainfall intensity during winter months, with the caveat that there is great spatial variability in the projections that may preclude downscaling to the project site drainage area, which is relatively small (WSDOT 2011). The project site crossing has been evaluated and determined to be a low risk site based on the Climate Impacts Vulnerability Assessment maps (Figure 50). Based on the determination of this location being a low risk site, no additional climate change design modifications were made. The new structures were designed so their foundations do not become exposed during the 500-year flow event. Also, hydraulic modeling indicated that the flow through the replacement culvert is not predicted to become pressurized (i.e., no freeboard) during the 500-year event.

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7.1 Climate Resilience Tools

WSDOT also evaluates crossings using the mean percent change in 100-year flood flows from the WDFW Future Projections for Climate-Adapted Culvert Design program. All sites consider the percent increase in peak flow estimated for 2080 throughout the design of the structure. Appendix I contains the information received from WDFW for this site.

7.2 Hydrology

For each design WSDOT uses the best available science for assessing site hydrology. The predicted flows are analyzed in the hydraulic model and compared to field and survey indicators, maintenance history, and any other available information. Hydraulic engineering judgment is used to compare model results to system characteristics; if there is significant variation, then the hydrology is reevaluated to determine whether adjustments need to be made, including adding standard error to the regression equation, basin changes in size or use, etc.

In addition to using the best available science for current site hydrology, WSDOT is evaluating the structure at the 2080 predicted 100-year flow event to check for climate resilience. The design flow for the crossing is 97.3 cfs at the 100-year storm event. The projected increase for the 2080 flow rate is 19.4 percent, yielding a projected 2080 flow rate of 116.2 cfs.

7.3 Climate Resilience Summary

A minimum hydraulic opening of 28 feet allows for extreme event flows to pass through the replacement structure safely under the projected 2080 100-year flow event. This will help to ensure that the structure is resilient to climate change and the system is allowed to function naturally, including the passage of sediment, debris, and water in the future.

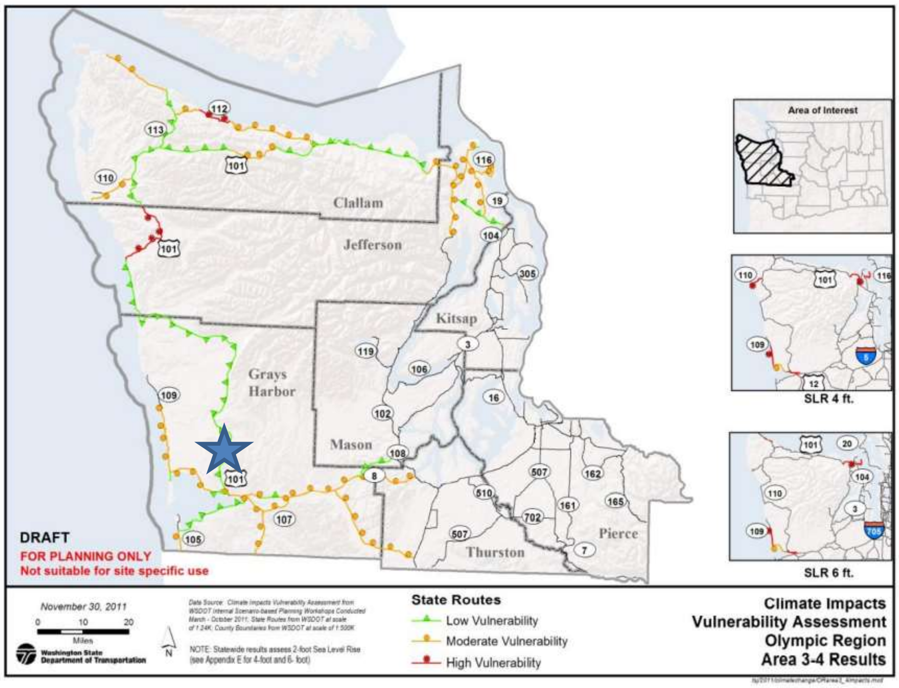

Figure 50: Climate impacts vulnerability assessment of Olympic Region areas 3 and 4 (source: WSDOT 2011). Site location is indicated by star

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8 Scour Analysis

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Total scour will be computed during later phases of the project using the 100-year, 500-year, and projected 2080 100-year flow events. The structure will be designed to account for the potential scour at the projected 2080 100-year flow events. For this phase of the project, the risk for lateral migration and potential for degradation are evaluated on a conceptual level. This information is considered preliminary and is not to be taken as a final recommendation in either case.

8.1 Lateral Migration

Based on the evaluation in section 2.8.5, the risk for lateral migration of the project stream is considered negligible.

8.2 Long-term Aggradation/Degradation of the Riverbed

Based on the evaluation in section 2.8.4, there is a little risk of long-term aggradation or degradation at the project site over the life of the replacement structure, largely because the design reconnects the upstream and downstream grades with negligible discontinuity in the longitudinal profile.

8.3 Local Scour

Three types of scour will be evaluated at this site: bend scour upstream and downstream of the replacement culvert, inlet scour, and contraction scour. Initial scoping level calculations indicate the amount of local scour will likely be small, on the order of 1 feet. These forms of scour will be evaluated in greater depth after the stream channel design has been finalized. It is anticipated that bend scour will be negligible at this site given the realignment that is proposed. Large wood pieces placed in the channel could have scour holes develop around the rootwad, which could lead to trapping and stranding in years when the stream goes dry during summer months.

Summary

Table 19 presents a summary of this PHD Report results.

Table 19: Report summary

Stream crossing category	Elements	Values	Report location
Habitat gain	Total length	3,811 LF	2.4 Site Description
BFW	Average BFW	14.4’	2.8.2 Channel Geometry
	Reference reach found?	Yes	2.8.1 Reference Reach Selection
Channel slope/gradient	Existing crossing	1.1%	2.8.4 Vertical Channel Stability
	Reference reach	1.1%	2.8.2 Channel Geometry
	Proposed	1.1%	2.8.4 Vertical Channel Stability
Countersink	Proposed	FHD	4.7.3 Freeboard
	Added for climate resilience	FHD	4.7.3 Freeboard
Scour	Analysis	FHD	8 Scour Analysis
	Streambank protection/stabilization	FHD	8 Scour Analysis
Channel geometry	Existing	Perpendicular	2.8.2 Channel Geometry
	Proposed	No Change	4.4.2 Channel Planform and Shape
Floodplain continuity	FEMA mapped floodplain	N	2.3 Floodplains
	Lateral migration	N	2.8.5 Channel Migration
	Floodplain changes?	Y	6 Floodplain Changes
Freeboard	Proposed	3.0'	4.7.3 Freeboard
	Added for climate resilience	No	4.7.3 Freeboard
	Additional recommended	0.0'	4.7.3 Freeboard
Maintenance clearance	Proposed	6.0'	4.7.3 Freeboard
Substrate	Existing	D_{50}=0.8” & Silt-Sand	2.8.3 Sediment
	Proposed	D_{50}=0.6”	5.1 Bed Material The streambed design considered the local characteristic grain size distribution (GSD) of gravel measured in the pebble count, standard streambed stability calculations for the proposed channel longitudinal and cross-section profile grading, and requirements of WAC 220-660-190. Two GSDs will be proposed for this site. One grain size distribution is for the streambed mix, which is presented in the section below,

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Stream crossing category	Elements	Values	Report location
			and the second is for proposed meander bars within the replacement structure. Partial channel-spanning meander bars are recommended within the proposed structure to encourage natural channel evolution and flow complexity within the constructed channel. The gradation for the proposed meander bars will be designed during the FHD phase. In addition, large woody material is proposed to be placed on and over the streambed to provide instream habitat complexity and overhead cover for fish. These two elements of the design are described in separate sections below.
Hydraulic opening	Proposed	28'	4.7.2 Minimum Hydraulic Opening Width and Length
	Added for climate resilience	N	4.7.2 Minimum Hydraulic Opening Width and Length
Channel complexity	LWM	Y	5.2 Channel Complexity
	Meander bars	Y	4.4.2 Channel Planform and Shape
	Boulder clusters	MAYBE	4.4.2 Channel Planform and Shape
	Mobile wood	N	5.2 Channel Complexity
Crossing length	Existing	87'	2.7.2 Existing Conditions
	Proposed	41'	4.7.2 Minimum Hydraulic Opening Width and Length
Floodplain utilization ratio	Flood-prone width	110'	4.2 Existing-Conditions Model Results
	Average FUR upstream and downstream	7.6	4.2 Existing-Conditions Model Results
Hydrology/design flows	Existing	Regress	3 Hydrology and Peak Flow Estimates
	Climate resilience	Yes	3 Hydrology and Peak Flow Estimates
Channel morphology	Existing	Stage 1	2.8.2 Channel Geometry
	Proposed	Stage 1	5.2 Channel Complexity
Channel degradation	Potential?	N	8.2 Long-term Aggradation/Degradation of the Riverbed
	Allowed?	Y	8.2 Long-term Aggradation/Degradation of the Riverbed
Structure type	Recommendation	N	4.7.1 Structure Type

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Stream crossing category	Elements	Values	Report location
	Type	NA	4.7.1 Structure Type

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Appendices

Appendix A: FEMA Floodplain Map

Appendix B: Hydraulic Field Report Form

Appendix C: SRH-2D Model Results

Appendix D: Streambed Material Sizing Calculations

Appendix E: Stream Plan Sheets, Profile, Details

Appendix F: Scour Calculations (to be completed at FHD)

Appendix G: Manning's Calculations (not used)

Appendix H: Large Woody Material Calculations

Appendix I: Future Projections for Climate-Adapted Culvert Design

Appendix J: Co-Manager Comments on Draft PHD Report and Stream Team Responses

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Appendix F: Scour Calculations

This appendix was not used because it is used for the FHD Report, not the PHD Report.

Appendix G: Manning’s Calculations

Appendix H: Large Woody Material Calculations

Appendix I: Future Projections for Climate-Adapted Culvert Design

Appendix J: Co-Manager Comments on Draft PHD Report and Stream Team Responses

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